Universidad Carlos III de Madrid

RHEINISCH-WESTFÄLISCHE TECHNISCHE HOCHSCHULE AACHEN

Diseño de una red de referencia para la evaluación de las mejoras de la capacidad de acogida de un sistema utilizando transformadores de distribución

Reference Grid Design for the Assessment of Integration Potential improvements using Voltage Regulated Distribution Transformers

Proyecto final de carrera realizado en

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1. Motivación y objetivos

Año tras año las energías renovables son más y más importantes en el marco de fuentes de obtención de energía. En este proyecto, se intenta dar un visión sobre la influencia de los sistemas fotovoltaicos y cómo podemos mejorar e incrementar la energía fotovoltaica obtenida en una red.

Se define potencial de integración (o capacidad de acogida) como la cantidad de potencia fotovoltaica instalada que puede ser conectada en una red de distribución sin necesidad de reforzarla.

Es una medida para evaluar las fortalezas y debilidades de las nuevas tecnologías como los transformadores reguladores de tensión.

En proyectos anteriores desarrolladas en el IFHT se han identificado los parámetros más influyentes en la capacidad de acogida utilizando transformadores reguladores de tensión.

El objetivo principal de este proyecto será obtener los parámetros más importantes y por tanto, más relevantes en el modelo para la evaluación de la capacidad de acogida, utilizando un método estadístico basado en la varianza llamado Extended Fourier Amplitude Sensitivity Test, y con estos parámetros, mejorar la capacidad de acogida en el modelo.

2. Fundamentos teóricos

En este capítulo se habla sobre los distintos conocimientos necesarios para comprender y realizar nuestro procedimiento. Se dará una visión de qué es la capacidad de acogida y, también, se hablará sobre los análisis de sensibilidad basados en la varianza, como los índices Sobol, método FAST y EFAST.

2.1. Capacidad de acogida

La capacidad de acogida es un método que permite realizar un análisis de la capacidad de red para aceptar una nueva carga o producción sin dañar ni poner en peligro el suministro de energía. [BOL11]

Se puede definir capacidad de acogida como la máxima cantidad de generación distribuida que es posible inyectar en un sistema eléctrico, respetando las condiciones de funcionamiento óptimo.

En la figura 1, se muestra una definición gráfica obtenida de [BOL11]. La capacidad de acogida es el punto crítico donde el índice de comportamiento obtiene su valor límite. Cuando este límite es superado, las condiciones de la red se considerarán inadmisibles. [BOL11]

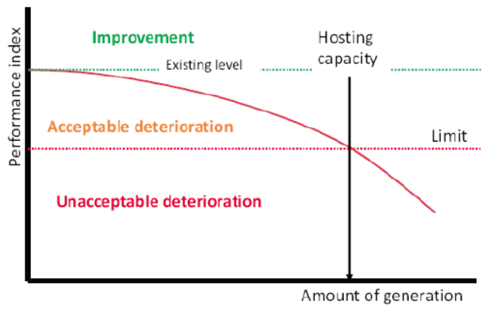

Figura 1: Cálculo de la Capacidad de Acogida a través de un solo índice de comportamiento. [BOL11]

2.1.1. Métodos para mejorar la capacidad de acogida

Restricción de la producción→ Consiste en la reducción de la potencia de salida de ciertas fuentes de energía al tiempo que el límite la capacidad de acogida es superada. Cuanto mayor sea el porcentaje de tiempo durante el que la restricción es aceptable, mayor será la cantidad de capacidad de acogida. [BOL11]

Línea dinámica de carga→ El límite de línea estática resulta de una estimación conservativa de la máxima corriente permitida. Es posible que la radiación absorbida pueda ser escasa en la mayoría del año, y eso, unido a bajas temperaturas, puede significar que la refrigeración del conductor sea significantemente mayor que el límite estático durante gran parte del año. [BOL11]

En la siguiente tabla se comparan los dos métodos.

Hosting Capacity :	**Current limited** [Power]	[Produced]	[Curtailed]
Present prod mix: no curtailment: *(85% produced energy is wind, 15 % hydro.)*)	130 MW	350 GWh	0
with curtailment: 2% (175h/year)	154 MW	410 GWh	7 GWh
: 5% (438h/year)	170 MW	455 GWh	27 GWh

Hosting Capacity :	**Current limited** [Power]	[Produced]
Present prod mix: no dynamic line rating: *(85% produced energy is wind, 15 % hydro.)*)	130 MW	350 GWh
With dynamic line rating	260 MW	700 GWh

Tabla 1: Comparación de los métodos de mejora de la capacidad de acogida de una red. [BOL11]

2.2. Análisis de sensibilidad

Un análisis de sensibilidad es el estudio de cómo la incertidumbre en las salidas de un modelo (numérico o de otro tipo) se puede atribuir a diferentes fuentes de incertidumbre en el modelo de entradas. [SAL08]

Es importante definir el factor o factores más influyentes en un modelo, porque normalmente, en un modelo real suele haber muchos parámetros de entrada, y muchas de estas entradas son despreciables para el modelo, para su salida. Con un análisis de sensibilidad podemos obtener el parámetro más importante a través de un modelo matemático, simplificando así el estudio del modelo.

2.2.1. Métodos basados en la varianza

Un análisis de sensibilidad basado en la varianza es una forma de análisis global de la sensibilidad de un modelo. Trabajando en un marco probabilístico, se descompone la varianza de la salida del modelo en fracciones que se pueden atribuir a las entradas o conjuntos de entradas del modelo. [SAL08]

Los métodos de análisis de sensibilidad basados en la varianza son importantes porque pueden medir la sensibilidad a través de todo el espacio de entradas. Pueden trabajar con entradas no lineales y medir el efecto de las interacciones en sistemas no aditivos.

La idea principal de estos métodos es cuantificar la cantidad de varianza que cada factor de entrada Xi contribuye a la varianza de la salida.

Los métodos de análisis de sensibilidad basados en la varianza se calculan siguiendo la descomposición ANOVA que se puede ver a continuación. [SOB05]

$$f(x) = f_0 + \sum_i f_i(x_i) + \sum_{i<j} f_{i,j}(x_i, x_j) + \cdots + f_{1,2\ldots n}(x_1, x_2, \ldots, x_n)$$

Fórmula 1: ANOVA como descomposición. [SOB05]

Los efectos más importantes son el efecto de primer orden y el efecto total, que son los que estudiaremos.

El efecto de primer orden es la contribución a la varianza del efecto principal de Xi, por tanto mide el efecto de cómo varia Xi solamente como promedio de variaciones en otros parámetros de entrada. [SOB93]

El efecto total mide la contribución a la varianza de salida de Xi, incluyendo todas las varianzas causadas por sus interacciones, de cualquier orden, con otras variables de entrada.

2.2.2. Índices de Sobol

Sobol [SOB93] definió el efecto de primer orden por descomposición de la función del modelo en sumandos de dimensionalidad creciente.

$$f(x_1 \dots, x_k) = f_0 + \sum_{i=1}^{k} f_i(x_i) + \sum_{i=1}^{k} \sum_{j=i+1}^{k} f_{i,j}(x_i, x_j) + \dots + f_{1,\dots k}(x_1, \dots, x_k)$$

Fórmula 2: Descomposición de la función del modelo por Sobol. [SOB05]

Para los índices de Sobol, la varianza total V(Y) se define como

$$V(Y) = \int_{\Omega^k} f^2(X)\, dx - f_0^2$$

Fórmula 3: Varianza total en Sobol. [EIK05]

Y podemos definir la varianza parcial como:

$$V_{i1\dots is} = \int_0^1 \dots \int_0^1 f_{i1\dots is}^2((x_{i1}, \dots, x_{is}) dX_{i1} \dots dX_{is}$$

Fórmula 4: Varianza parcial. [EIK05]

Dónde $1 \leq i_1 < \dots < i_s \leq k$ y s=1… k

Por último, los índices Sobol se definen mediante:

$$S_{i1\dots is} = \frac{V_{i1\dots is}}{V(Y)}$$

Fórmula 5: ïndices Sobol. [EIK05]

2.2.3. Fourier Amplitude Sensitivity Test (FAST)

FAST es un procedimiento que proporciona un modo de estimar el valor esperado y la varianza de la variable de salida y la contribución individual de factores de entrada a dicha varianza, básicamente a través de una curva de búsqueda que rastrea todo el espacio de las entradas. Una ventaja que tiene FAST es que la estimación de la sensibilidad puede ser realizada independientemente para cada factor usando un mismo conjunto de repeticiones en virtud de que todos los términos en una expansión de Fourier son mutuamente ortogonales. [SAL98]

La idea principal del método FAST es transformar la integral k-dimensional en el dominio de x en integrales unidimensionales en el dominio de s, utilizando una función de transformación.

$$x_i = G_i \cdot (\sin(\omega_i s)) \quad para\ i = 1 \ldots n$$

Fórmula 6: Transformation function. [SAL99]

La esperanza de la variable Y será:

$$E(Y) = \frac{1}{2\pi} \int_{-\pi}^{\pi} f(s) ds$$

Fórmula 7: Esperanza de Y. [EIK05]

Dónde: $f(s) = f(G_1(sin(\omega_1 s)) \ldots G_k(sin(\omega_k s)))$

Utilizando las propiedades de Fourier, podemos obtener una aproximación de la varianza de Y como:

$$Var(Y) = \frac{1}{2\pi} \int_{-\pi}^{\pi} f^2(s) ds - [E(Y)]^2 \approx \sum_{j=-\infty}^{\infty} \left(A_j^2 + B_j^2\right) - (A_0^2 + B_0^2) \approx 2 \sum_{j=1}^{\infty} \left(A_j^2 + B_j^2\right)$$

Fórmula 8: Variance of Y. [EIK05]

Dónde A_j y B_j son los coeficientes de Fourier

$$A_j = \frac{1}{2\pi}\int_{-\pi}^{\pi} f(s)\cos(js)ds \qquad B_j = \frac{1}{2\pi}\int_{-\pi}^{\pi} f(s)\sin(js)ds$$

Fórmula 9: Coeficientes de Fourier. [EIK05]

La contribución de X_i en la varianza total de Y se aproxima para un tamaño de muestra mínimo de $N_s=2M\omega_{max}+1$, por:

$$D_{\omega i} \approx \sum_{p=1}^{\infty}(A_{p\omega i}^2 + B_{p\omega i}^2)$$

Fórmula 10: Varianza individual. [SAL98]

Y el índice de sensibilidad global será:

$$S_i = \frac{2\sum_{p=1}^{\infty}(A_{p\omega i}^2 + B_{p\omega i}^2)}{2\sum_{j=1}^{\infty}\left(A_j^2 + B_j^2\right)} = \frac{D_{\omega i}}{D_{FAST}}$$

Fórmula 11: Índice de sensibilidad global en FAST. [SAL98]

Es destacable que Cukier, Koda and Saltelli, desarrollaron funciones de transformación, G_i. [SAL99]

Cukier→ $x_i = \overline{x}_i \cdot e^{\overline{v}_i \sin(\omega_i s)}$

Koda→$x_i = x_i(1 + \overline{v}_i \sin(\omega_i s)$

Saltelli→ $x_i = \frac{1}{2} + \frac{1}{\pi} sin^{-1}(\sin(\omega_i s))$

2.2.4. FAST Extendido (EFAST)

Saltelli propuso una mejora del método FAST para estimar el efecto total como ocurre en los índices de Sobol. Este método se llama Extended Fourier Amplitude Sensitivity Test.

En EFAST, podemos calcular el efecto total mediante la estimación de la varianza en el grupo complementario, V_{ci}^{FAST}, definido por: [EIK05] [SAL99]

$$\hat{V}_{ci}^{FAST} = 2\sum_{p=1}^{M}\left(A_{p\omega_{\sim i}}^{2} + B_{p\omega_{\sim i}}^{2}\right)$$

Fórmula 12: Varianza del grupo complementario. [EIK05]

También es necesario introducir un desfase en la función de transformación.

$$X_i(s) = G_i(\sin(\omega_i s)) = \frac{1}{2} + \frac{1}{\pi}\arcsin(\sin(\omega_i s + \varphi_i))$$

Fórmula 13: Función de transformación de Saltelli en EFAST. [EIK05]

3. Metodología

El objetivo principal de esta tesis es la obtención de los parámetros más importantes de la red mediante el uso de un enfoque matemático. La obtención de la más importante, el parámetro más relevante de la red, es posible cambiar su valor para tratar de optimizar el potencial de integración y, por lo tanto, aumentar la energía fotovoltaica instalada en la red, que es una meta importante para obtener más y más energías renovables en nuestro modelo

Como se menciona en el capítulo 2, existen diferentes métodos de análisis de sensibilidad para estudiar el efecto de primer orden y el efecto total del modelo, pero en este caso, se utiliza un método basado en la varianza. Los métodos de análisis de sensibilidad basados en la varianza más importantes son los índices de Sobol y el método FAST Extendido (EFAST).

EFAST resuelve los problemas que aparecen en FAST al utilizar datos no lineales y no monótonos. EFAST puede considerarse como un método cuantitativo para el análisis global de sensibilidad en experimentos numéricos. Esto significa que EFAST puede clasificar diferentes parámetros de un modelo real en orden de importancia.

3.1. Implementación

A continuación, se explica el procedimiento utilizado para crear las diferentes redes, y asi, poder evaluar los parámetros más influyentes del modelo. Para este fín, se utilizan tres códigos de MATLAB. El primer código es „EFAST_Analyse.m“ (ver appendix A) donde se crean las diferentes redes siguiendo las características del proceso de EFAST y cumpliendo con la normativa vigente en Alemania (red en la que nos basamos).

En segundo lugar se utiliza el código „Versuchsdurchfuehrung.m" para simular y obtener resultados para las distintas redes. En estos resultados obtenemos los valores de la red como la cantidad de energía fotovoltaica, el tipo de nodo, la tensión mínima y máxima entre otros.

Finalmente con estos valores realizamos el análisis de sensibilidad utilizando el código de „EFAST_Austwertung“(ver appendix B). En este código obtenemos el efecto de primer orden y el efecto total que tiene cada parámetro en el modelo.

Es de destacar que para los desarrollos de los códigos „EFAST_Analyse“ y „EFAST_Austwertung“ se utiliza un procedimiento similar al seguido en „Eikos. A simulation Toolbox for Sensitivity Analysis“ [EIK05] pero adaptándolo a nuestro modelo, haciendo cambios como el número de curvas de búsqueda, la transformación de los datos aleatorios de entrada creados entre otros.

Hay que tener en cuenta que en „EFAST_Analyse“ se crean las muestras de redes que utilizaremos para posteriormente hacer el estudio de sensibilidad. El tamaño de la muestra es variable y podemos modificarlo utilizando la variable „WantedN“. En los resultados posteriores hemos utilizado muestras de 1000, 5000, 7500, 10000, 12500 y 15000. (Como se puede ver en Appendix C)

En nuestro modelo hay 10 parámetros de entrada, que son:

- Longitud de la radiación solar (Length of the radiation power)
- Número de cargas en la subestación (Number of departures from the local substation)
- Tipo de transformadores (Apparent power of the transformer)
- Distancia entre cargas (Distance of the link node)
- Tipo de línea (Line type)
- Penetración de la carga según el tipo de vivienda (Penetration of load types):
    - Viviendas unifamiliares (Single-family homes (SFH))
    - Apartamentos de viviendas (Small apartment buildings (SAP))
    - Granjas (Farms)
- Factor de aplicación de carga (Load application factor)
- Factor de inhomogeneidad (Inhomogeneity factor)

Para la creación de las redes aleatorias es necesario utilizar la transformación de Saltelli proporcionada para FAST Extendido.

$$X_i(s) = G_i(\sin(\omega_i s)) = \frac{1}{2} + \frac{1}{\pi}\arcsin(\sin(\omega_i s + \varphi_i))$$

Fórmula 14: Función de transformación de Saltelli en EFAST. [EIK05]

Tras crear estas redes aleatorias, se aplica una transformación lineal, que se divide en tres partes: para datos discretos, datos no discretos y para los datos de penetración.

Finalmente se borran los datos de redes invalidas y se guardan los datos en diferentes carpetas para cada parámetros dentro de la carpeta „Berechnungsfaelle".

Después se utiliza „Versuchsdurchfuehrung"para obtener resultados válidos para nuestras redes y así poder realizar posteriormente el análisis de sensibilidad que se desarrolla en „EFAST_Austwertung".

Es importante destacar que en „EFAST_Austwertung" la variable „fillwithzeros" rellena, o no, con ceros los vectores cuando se borra una red no válida. Es relevante tener en cuenta las redes no válidas porque sin "fillwithzeros" estas redes desaparecen del estudio y, es obvio que estas redes también influyen en el sistema, mientras que utilizando "fillwithzeros", estas redes no válidas son consideradas como nulas.

Para la obtención de los efectos se utiliza los coeficientes de Fourier:

$$A_j = \frac{1}{2\pi} \int_{-\pi}^{\pi} f(s) \cos(js)\, ds \qquad B_j = \frac{1}{2\pi} \int_{-\pi}^{\pi} f(s) \sin(js)\, ds$$

Fórmula 15: Coeficientes de [EIK05]

Y se obtiene la varianza individual y total utilizando las expresiones dadas en el capítulo 2.

4. Resultados

4.1. Análisis de sensibilidad

Se han realizado diferentes simulaciones con tamaños de muestra distintos: 1000, 5000, 7500, 10000, 12500, 15000. Se han utilizado estos tamaños de muestra diferentes para comparar los resultados y saber si el proceso es óptimo en muestras pequeñas.

Los resultados obtenidos para cada tamaño de muestra se encuentran en las tablas adjuntas en el Appendix C.

Los resultados obtenidos para el efecto de primer orden se pueden observar en las siguientes gráficas. Nótese que se diferencian dos procesos, utilizando la variable fillwithzeros y sin utilizarla.

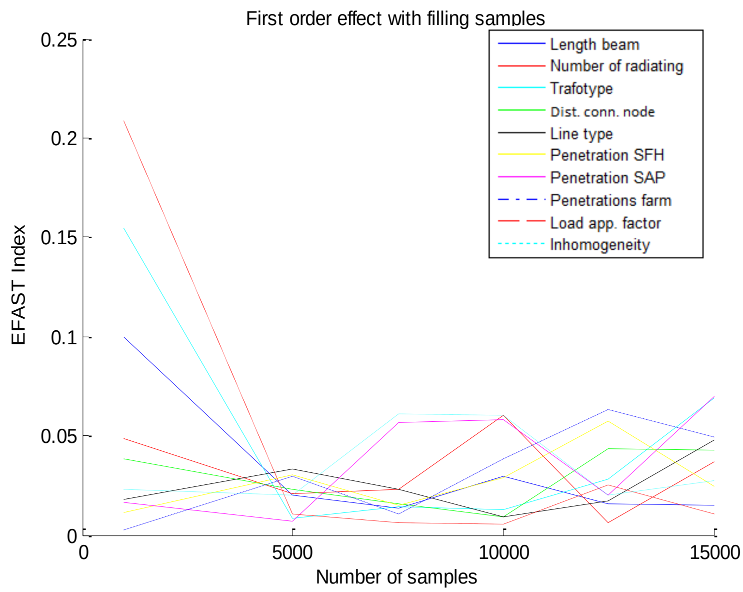

Figura 2: Efecto de primer orden utilizando fillwithzeros en EFAST

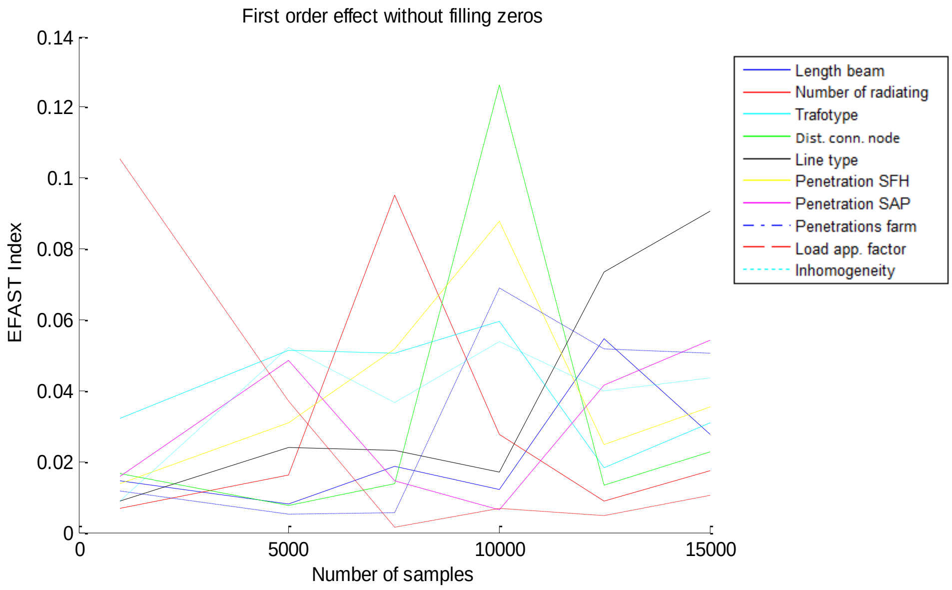

Figura 3: Efecto de primer orden sin utilizar fillwithzeros en EFAST

Observando las gráficas, es notable que en ambos casos cuando hay un número de tamaño de muestra menor, el parámetro más relevante es el número de radiaciones. Al aumentar el tamaño de muestras, la penetración va tomando mayor relevancia.

Tiene más sentido los resultados obtenidos utilizando fillwithzeros, ya que rellenamos de 0 las redes inválidas en lugar de borrarlas, teniéndolas en cuenta, y es obvio, que aunque sean inválidas, se deben tener en cuenta.

En ambos casos hay que destacar que los resultados no dan resultados como se esperaba. En la siguiente sección se comparan el método EFAST y los índices de Sobol que fueron desarrollados por Stefan Seeman

4.2. Comparación con índices de Sobol

En este apartado compararemos el efecto de primer orden en el método EFAST y en los índices de Sobol [SEE13].

En las gráficas anteriores se puede observar el valor del efecto de primer orden en EFAST para el caso de relleno con ceros en lugar de las redes no válidas, y en el caso de borrar estas redes no válidas.

La siguiente gráfica muestra el efecto de primer orden obtenido mediante los índices de Sobol. [SEE13]

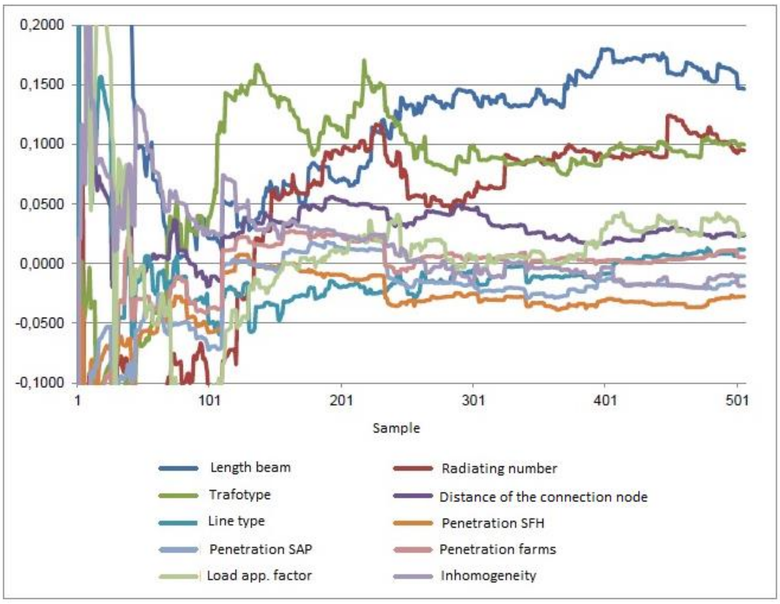

Figura 4: Efecto de primer orden en los índices de Sobol [SEE13]

Comparando las gráficas, es obvio que son demasiado diferentes. La tendencia y los valores cambian de un método a otro. Es razonable que las gráficas no sean iguales tanto en el método EFAST como en los índices de Sobol ya que no se tratan del mismo método, pero el hecho de que los valores no sean aproximados, hecho que sí debería ocurrir, nos hace pensar que es posible que haya fallos en el método EFAST que hemos desarrollado. Las posibles fuentes de error se discuten en el próximo apartado.

En las siguientes gráficas se comparan los valores de convergencia de los dos métodos, donde podemos observar que los dos métodos no trabajan en el mismo rango de valores, lo que significa, como acabamos de mencionar, que es posible que haya errores en nuestro código.

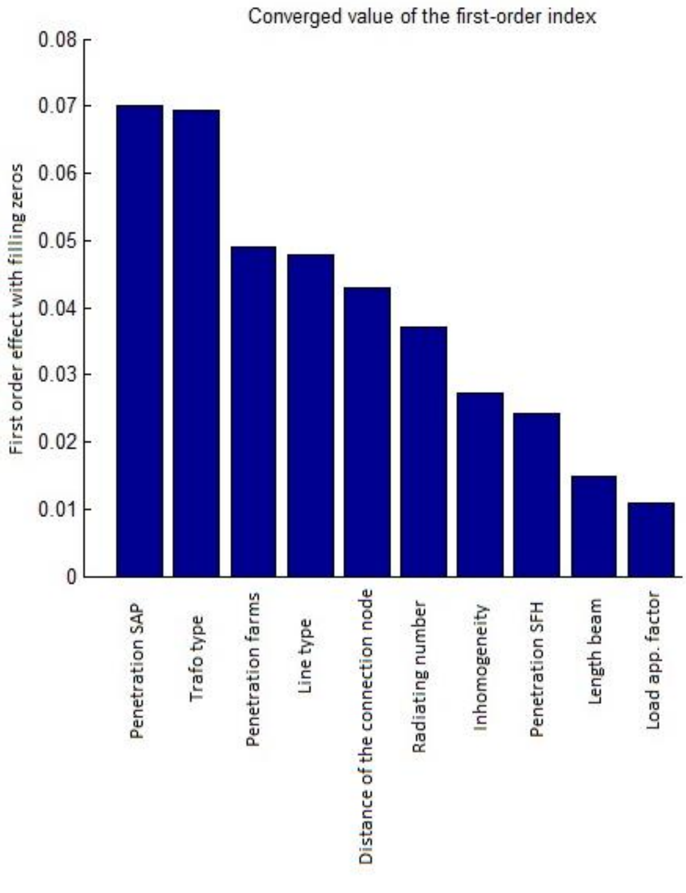

Figura 5: Valores de convergencia del efecto de primer orden para el método EFAST con relleno de ceros (utilizando fillwithzeros)

A raíz de los últimos gráficos, el parámetro más importante utilizando EFAST con relleno de ceros redes en lugar no válidos son: la penetración de pequeños edificios de apartamentos, el tipo de transformadores, esto es en función de la potencia aparente del transformador, y la penetración de las explotaciones. Es evidente que la penetración de las cargas es muy importante en una red y en este caso EFAST demuestra.

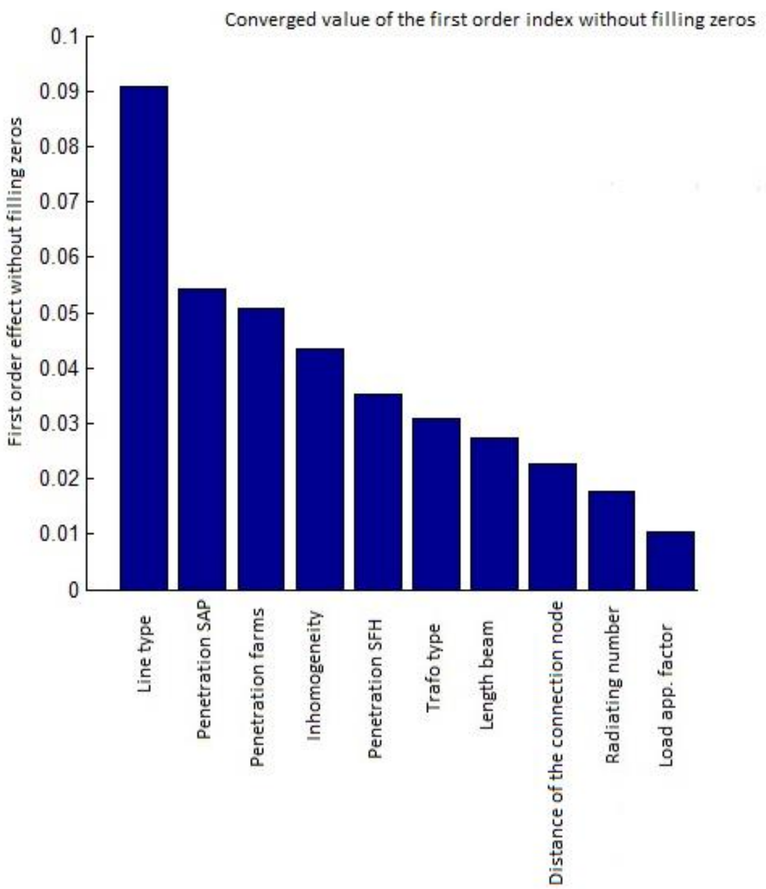

Figura 6: Valores de convergencia del efecto de primer orden para el método EFAST sin relleno de ceros (sin utilizar fillwithzeros)

En el caso de EFAST sin relleno de ceros, los parámetros más importante son el tipo de línea, la penetración de pequeños edificios de apartamentos y la penetración en las granjas. Es notable que el único parámetro que cambia, es el tipo de línea que es el parámetro con el valor más alto de la convergencia efecto de primer orden (0,09).

Los valores de convergencia para el efecto de primer orden obtenido mediante el uso de índices de Sobol se presentan en el siguiente gráfico. [SEE13]

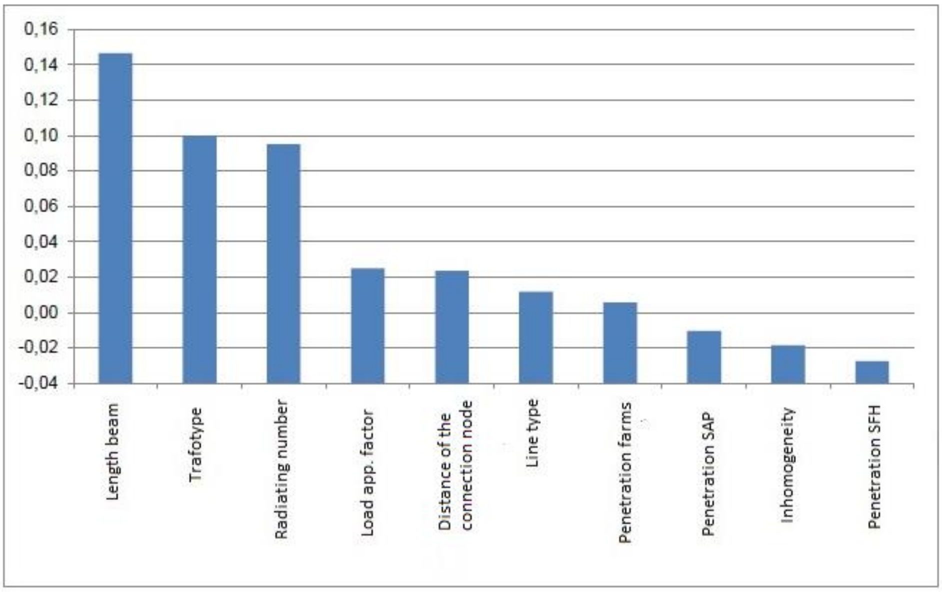

Figura 7: Valores de convergencia para los índices de Sobol. [SEE13]

En este caso los parámetros más relevantes son: longitud de la viga, tipo de transformador y el número de radiación, esto es el número de salidas desde la subestación local. Como se mencionó en la sección anterior, la diferencia entre los índices de Sobol y EFAST puede ser debido a la presencia de errores en nuestro desarrollo del modelo.

4.3. Posibles fuentes de error

Como se menciona anteriormente, los resultados obtenidos no son tan satisfactorios como deberían por lo que es posible que en el código haya errores que produzcan estos fallos. En este apartado indicamos las posibles fuentes de error.

- **Número de muestras→** Se puede observar que las gráficas obtenidas con el método EFAST y las obtenidas con los índices de Sobol no son iguales, incluso la tendencia es completamente diferente. Tal vez el hecho de utilizar en los índices Sobol la función „Sobolset“ sea una diferencia importante entre ambos métodos ya que con „Sobolset“ se crean muestras para cada punto de la red y los gráficos se obtienen de forma continuada, mientras que en EFAST tenemos valores para tamaños de muestra concretos.

- **Errores matemáticos→** EFAST utiliza derivadas e integrales (cálculos infinitesimales de una función modelo) para encontrar los datos sobre la distribución asociada a cada factor de entrada y para el caso de datos discretos, EFAT busca en espacios finitos. Este enfoque da lugar a que el método puede ser poco fiable debido a la complejidad de las operaciones.

- **Número de entradas→** Es importante saber que cuando EFAST se aplica a modelos con muchos parámetros de entrada el nivel de ruido debido a las interacciones entre las variables es alto en comparación con otros métodos basados en la varianza como Sobol o Jansen. Esto explica que otros parámetros (sin gran relevancia en el modelo) pueden aumentar la incertidumbre en el modelo debido a la presencia de interferencias en el muestreo de EFAST. Este error debería ser investigado en profundidad en futuros estudios.

- **Transformación de datos→** En los índices de Sobol se utiliza una transformación lineal de los datos y en el caso de EFAST este mismo tipo de transformación es utilizada (en concreto en EFAST_Analyse) pero se debe recordar que EFAST utiliza coeficientes de Fourier, entonces nuestro rango de trabajo está entre $-\pi$ a π, y en Sobol, entre 0 a 1. Tal vez es necesario otro tipo de transformación para ajustar mejor nuestro modelo y también para hacerlo más realista.

- Una de las posibles soluciones para el código podría ser encontrar otra transformación, otro tipo de interpolación que se ajuste a los valores sinusoidales. Se debe profundizar en Fourier y sus transformaciones.

4.4. Conclusiones

A la vista de los resultados y la comparativa con los índices de Sobol es evidente que el método EFAST que hemos desarrollado no funciona de forma correcta, y por lo tanto, es imposible predecir qué parámetros es el más importante en el modelo. Es cierto que los resultados teniendo en cuenta la variable „fillwithzeros“ da resultados más óptimos y nos puede ayudar a hacernos una idea de qué parámetros es el más influyente, pero aun así no se puede garantizar el buen funcionamiento del programa.

Los métodos basados en la varianza como los índices de Sobol y el método EFAST pueden ayudar mucho para decidir qué parámetros es posible cambiar para mejorar el sistema y aumentar la cantidad de energía fotovoltaica en el sistema, utilizando una simulación del sistema y un enfoque matemático.

Desafortunadamente EFAST no funciona correctamente pero creo que con el tiempo suficiente podemos hacer que el método funcione con el fín de simplicar el modelo para analizar la red y sus parámetros.

Puede ser interesante utilizar más tiempo para tratar de resolver los errores que haya en el código, centrándose sobre todo en las fuentes de error que se facilitan en el punto 4.3

Reference Grid Design for the Assessment of Integration Potential improvements using Voltage Regulated Distribution Transformers

Entwicklung von Referenznetzmodellen zur Bewertung der Steigerung des Integrationspotenzials durch regelbare Ortsnetztransformatoren.

Master Thesis

at

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Declaration

I hereby declare that the submitted Thesis has been a result of individual efforts, with no external aid, except for the assistance received at the Institute for High Voltage Technology.

The literature used has been categorically listed.

Aachen, 26th September 2014

Abstract

Year by year renewable energies are more and more important. In this thesis, it is tried to give an overview on photovoltaics systems, and how can improve and increase the PV in a network.

The installed power of photovoltaic systems which can be connected to an existing distribution grid without any reinforcements is called integration potential (IP).

It is a valid measure to assess strenghts and weaknesses of new technologies such as the voltage regulated distribution transformer (VRDT).

Previous thesis from IFHT have identified critical parameters influencing the integration potential using VRDT.

The main goal of this thesis will be to obtain the most relevant and important parameters in the model for IP assessment, by using a variance-based method called Extended Fourier Amplitude Sensitivity Test, and with this parameters, improve the Integration Potential in the model.

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1 Motivation and goals

Renewable energies are more and more important annually therefore countries should invest in this kind of energies as photovoltaic, wind or hydropower .

It is important to decrease the levels of pollution in the world and, also, it is important to not depend on non renewable energies belongs to a few countries as Saudi Arabia, Venezuela, Russia...which can decide to increase and increase the price of their fossil fuel reserves.

In this thesis, a variance-based method is studied with the aim to obtain the most important parameters in a model. It is possible to make changes in this parameters to improve the network and increase the quantity of PV installed. Therefore it can be increased the quantity of renewable energy absorbed.

The variance-based method used will be Extended Fourier Amplitude Sensitivity Test which is an improvement of Fourier Amplitude Sensitivity Test.

It is remarkable that the EFAST method can be used for identify the most important parameters in different models, but the results obtained are be based on the german network.

2 Theoretical basics

In this section the necessary knowledge to understand our task are presented. A vision of what is and how depends on different parameters, and the calculation of IP are given. Also different types of variance-based sensitivity analysis, as Sobol indices, Fourier Amplitude Sensitivity Test, are presented.

2.1 Integration Potential

2.1.1 Definition

Integration Potential (IP) is a method that permits to figure out the capability of the grid to accept new load or production ensuring the performance of the network in an appropriate state without endangering the power supply.

A graphic definition of the IP is shown in figure (1). The Integration Potential is the point where the performance index has just the same value as the limit and therefore, when this point is overtaken the behavior of the network will become unacceptable. [BOL11]

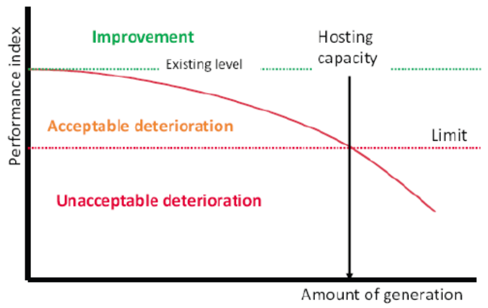

Figure 8: Determination of IP with a single performance index. [BOL11]

Integration Potential of a decentralized energy conversion system of a network is the sum of output of all generating plants which can be installed using the existing resources and the existing supply task without violating the normative of the country and the technical specifications.

2.1.2 Methods to improve Integration Potential

Curtailment of production→ Consist on reducing the power output from certain energy resources at time when the Integration Potential otherwise would be exceeded. The higher the percentage of time during, which curtailment is acceptable, the higher is the amount of production capacity that can be connected to the grid. [BOL11]

Dynamic line loading→The static line limit results in a conservative estimate of the maximum current permitted. It is possible that the radiation may be sparse for much of the year and together with a low temperature can mean that the cooling of the conductor would be significantly greater than the static limit for much of the year. Solar irradiance, wind and temperature measurements can be calculated for overhead lines based on IEEE Std. 738-2006.[BOL11]

The dynamic line rating gives much larger increase in hosting capacity than the production curtailment method.

Comparing both methods reveals that the dynamic line rating gives much larger increase in hosting capacity than the production curtailment method. It is possible to use both methods at the same time.

These differences are observed in the following table.

Hosting Capacity :	Current limited [Power]	[Produced]	[Curtailed]
Present prod mix: no curtailment: *(85% produced energy is wind, 15 % hydro.)*	130 MW	350 GWh	0
with curtailment: 2% (175h/year)	154 MW	410 GWh	7 GWh
: 5% (438h/year)	170 MW	455 GWh	27 GWh

Hosting Capacity :	Current limited [Power]	[Produced]
Present prod mix: no dynamic line rating: *(85% produced energy is wind, 15 % hydro.)*	130 MW	350 GWh
With dynamic line rating	260 MW	700 GWh

Table 2: Comparison dynamic line and curtailment of production. [BOL11]

2.1.3 Calculation of integration potential

In this section the calculation of integration potential by using an algorithm is given.

The definition given in 2.1.1 is diffuse in the sense that as this value has a strong dependence on the distribution of the facilities in the network. This dependence results from the contribution of a generator for whole voltage range which is caused by the impedance between local substation and the grid connection point and therefore it is a function of location. In addition to this spatial dependence, it is also remarkable the dependence of the voltage contribution of the installed capacity of the plants, which determines on the injected current. [SEE13]

Assuming a random map and also random system performance, the value for the integration potential of a network with a multiple calculation would vary greatly, what terms of the sensitivity analysis contradicts.

For the spatial dependence it should take into account that the voltage is twice as large for the same plant performance, the cable length between distribution transformer and plant doubles in a network area with just one machine. Analogously, for the same allowable voltage swing only half of the power plant is installed.

This problem can be countered with the assumption of a homogeneous plant distribution (and performance). Homogeneous distribution system in this context means that each load node of the network has a generating plant. Homogeneous system performance describes the assumption that the facilities of a network beam over the same installed power feature. [SEE13]

These assumptions lead to an underestimation of the potential integration of the network with optimal distribution of plants and which are overestimating it in the opposite case. It is remarkable that the determination of the optimal or unfavorable conditions for the integration potential of a network is not trivial, and these doubts even may differ from network to network. The assumption of homogeneous distributions and plant services is chosen to obtain a clear definition for the evaluation of the parameter VRDT, which leads to the same results even with repeated calculation of a network and is not dependent on network structure and supply task. Only in this way is possible a systematic investigation of the potential for integration of decentralized energy conversion systems in the context of a sensitivity analysis.

2.1.3.1 Calculation algorithm

To calculate the integration potential of a network, it is assigned to each node a photovoltaic plant of 30 kWp and it simulates the network via the two highest solar irradiations days of the year. The installed capacity of the plant is set to 30 kWp, as it is seen up to this plant performance of the service connection, as the most favorable network junction. [SEE13]

The used tool for power flow calculation simulates the power in 15-minute increments using probabilistic load profiles, standard load profiles and a model for photovoltaic system that generates depends on climatic data Rectifier profile. The climatic data come from the TRY regions of the German Weather Service, which divide Germany into 15 regions with homogeneous climatic conditions.

To simulate the TRY-Region 6 is used, in which is Aachen. The supply task, so the behavior of the loads and feeders of the network is simulated very realistically in this way.

For each quarter hour of the simulation, the sum of the load node calculated from load and injection assigned to the nodes, then a check of the voltage swing and loading of equipment occurs (see criteria in section 2.3). [SEE13]

Internally the power exists in two different states: Firstly, the state of the network without VRDT and secondly the state of the network with VRDT. This distinction is important because each different condition apply to both states about the valid voltage range, which affect the installed capacity of PV systems in each network state. For both networks, the algorithm proceeds as shown in Figure (11).

To check the criteria, a power flow calculation of the network is performed, first without distributed generators to obtain the node voltages, which serve as the basis for the network without VRDT. Finally, the power flow statements of the networks with distributed generation and a subsequent comparison of the node voltages and resource utilization with the respective criteria occur.

If a resource overload or a violation of the valid voltage range is detected, the algorithm reduces, depending on the fail, the installed capacity of all the plants of a particular beam power by 1%. The choice of the beam power is subject to the following factors: [SEE13].

- In resource overload

  - Transformer: power beam with the highest summed feed.

  - Line: power beam on which the violation was found.

- If voltage ligament injury

  - Power beam on which the violation was found.

These actions are repeated until a valid operating state is reached. After, the calculation of the next quarter hour of the day takes place using the adjusted equipment services performance. The procedure is carried out simultaneously for the network state with and without VRDT thus the use of the same probabilistic load profiles of consumers is assured in both network conditions. The accumulated installed capacity of photovoltaic systems of both states at the end of the simulation is the integration potential which represents the difference between the sums of the additional capacity due to the use of VRDT.

The procedure for this algorithm has two main advantages: Firstly, the uniform adjustment of the generator performance a change in the producer attack factor avoided and thus determines the integration potential of the networks under steady state conditions. Secondly, the adaptation of the plant performance in only one direction prevents a potential swing of the summed PV output to the value at which precisely the criteria are met again, an efficient use of the available computing time is possible.

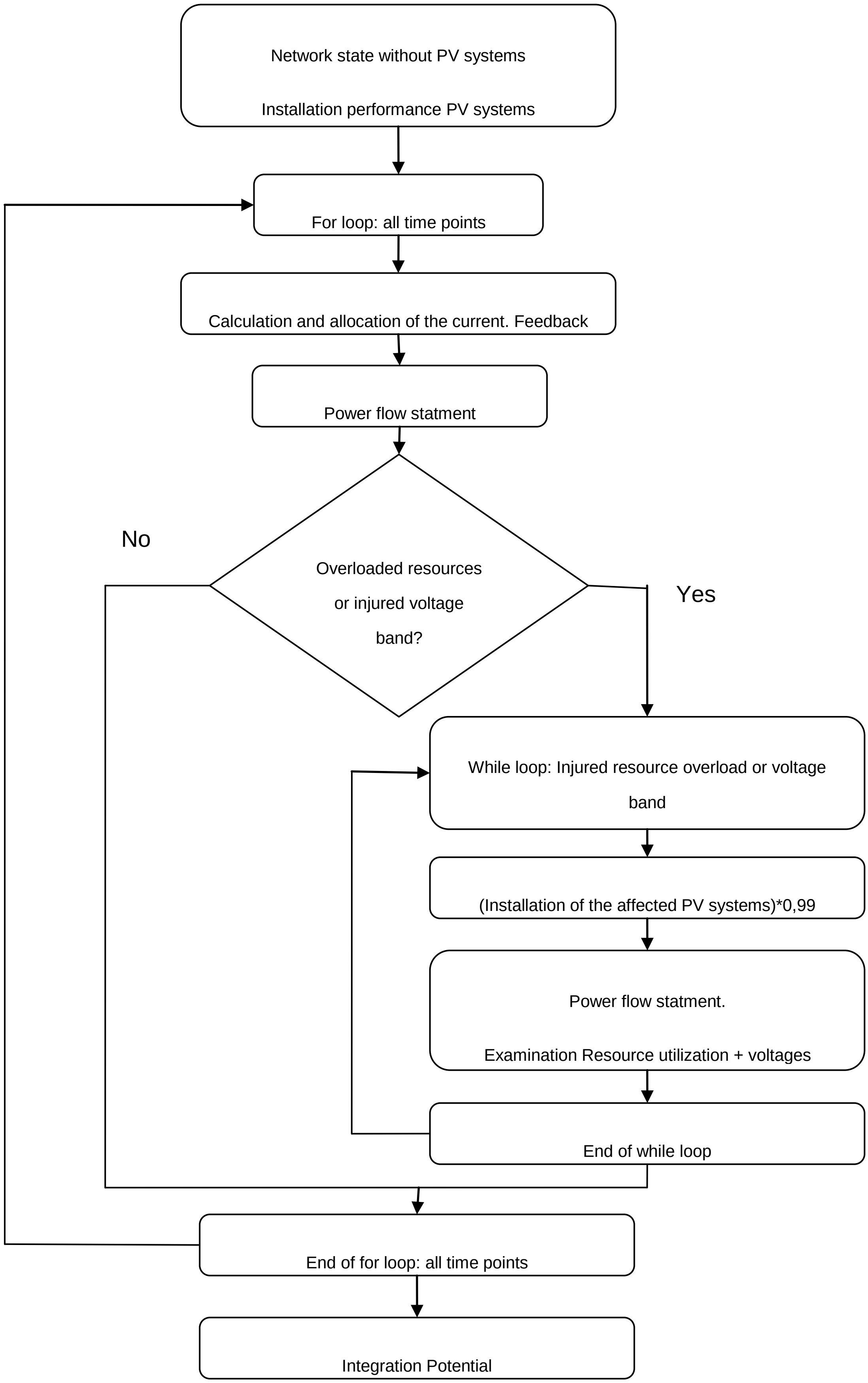

Figure 9: Flow chart of the algorithm for determining the integration potential of a network. [SEE13]

2.1.4 Criteria for calculation of additional integration potential

In this section the main criteria to determine the integration potential are developed. Basically is that the change in the supply problem by the integration of distributed generators must not lead to a situation in which the normative and technical specifications are violated [SEE13]. These are valid for networks with and without VRDT alike, with the difference that in networks with VRDT limiting the voltage swing on the VDE 4105 port is not relevant. Thus, the requirements of DIN EN 50160 are in this work for networks with VRDT terms of voltage quality significantly, thus limiting the slow voltage changes to ± 10 % U_n.

In this case, the voltage resulting from the technical design of the VRDT and its behavior in medium voltage networks gives different limits for the allowable voltage bandwidth in the network with VRDT. First, it must distinguish between a VRDT with busbar scheme and a VRDT with remote sensors.

The VRDT with remote sensor has full information about the network state and could use his entire control range for the compensation of voltage fluctuations along the rays of the network thus at a constant mean stress of 100% $U_{n,MS}$. Differs from the voltage on the high voltage side of VRDT from the nominal value, a portion of the control bandwidth needed to reach this difference must be used, then the integration of distributed generators only a correspondingly smaller voltage bandwidth can be made available. Figure (9) shows an example of voltage profile in a network with VRDT and remote sensing.

The control range is ± 10 % U_n during a possible voltage on the high voltage side of 100% and 105% $U_{n,MS}$, which would result in a voltage range of 20% and 15% for the integration decentralized generators. [SEE13]

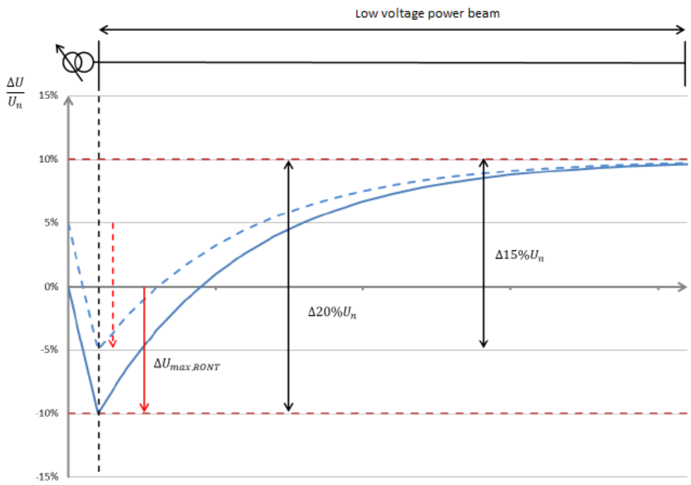

Figure 10: Voltage criteria of integration of distributed generators using VRDT with remote sensor. [SEE13]

For VRDT with busbar scheme, the voltage in the busbar is regulated to a specified target value. It is believed that this set value of the rated voltage corresponding to the low voltage network. If the voltage change on the high voltage winding is greater than the maximum setting range of the transformer, the medium voltage network in this case has only an influence on the tension band, which is that the integration of distributed generators are available . If this is not the case, there are a voltage increase of 10% $U_{n,MS}$ and the control bandwidth available shown in Figure (10). [SEE13]

Figure 11: Voltage criteria of integration of distributed generators using VRDT with busbar schemes. [SEE13]

For the calculation of the additional integration potential, a voltage regulated distribution transformer is used with busbar scheme and an infinitesimal small step voltage are adopted to simplify the network.

For the resource is defined, that they may be charged up to its maximum rated apparent power. In the literature, although often assumed that short-term overloads can be tolerated due to high concurrency and high potential duration of the supply of photovoltaic systems is, however, except in this work it and thus made an assessment on the safe side.

Overall, the criteria used to calculate the additional network recording capability to give the values listed in Table 2. [SEE13]

Criteria	Value without VRDT	Value with VRDT
Permissible voltage swing	≤ 3 % $U_{withoutDEA}$	≤ 10 % U_n
Allowable resources utilization	≤ 100 % S_n	≤ 100 % S_n

Table 3: Criteria for calculation of additional integration potential. [SEE13]

2.2 Sensitivity Analysis

2.2.1 Definition

Sensitivity Analysis (SA) is “the study of how uncertainty in the output of a model (numerical or otherwise) can be apportioned to different sources of uncertainty in the model input” [SAL08].

It is important to define the most influential factors in the model, because usually there are a lot of input variables, and many inputs have negligible effects or can be redundant for our output model. With a sensitivity analysis, the most important inputs can be obtained through a mathematical model, simplifying the study and therefore the model.

2.2.2 Variance based methods

Variance-based sensitivity analysis is a form of global sensitivity analysis. Working in a probabilistic framework, it decomposes the variance of the output of the model into fractions which can be attributed to inputs or sets of inputs. [SAL08]

Variance-based measures of sensitivity are attractive because they measure sensitivity across the whole input space (i.e. it is a global method), they can deal with nonlinear responses, and they can measure the effect of interactions in non-additive systems.

The main idea of the variance-based methods is to quantify the amount of variance that each input factor Xi contributes with on the unconditional variance of the output

Sensitivity indices of a variance-based method are calculated via ANOVA like decomposition of the function for the analysis. The general expression of ANOVA-like decomposition is: [SOB05]

$$f(x) = f_0 + \sum_i f_i(x_i) + \sum_{i<j} f_{i,j}(x_i, x_j) + \cdots + f_{1,2\ldots n}(x_1, x_2, \ldots, x_n)$$

Formula 16: ANOVA like decomposition. [SOB05]

It is remarkable that there are different orders in the SA. The most important are the first order and the total effect.

The first order effect is the contribution to the output variance of the main effect of X_i, therefore it measures the effect of varying X_i alone, but averaged over variations in other input parameters. [SOB93]

The total effect measures the contribution to the output variance of X_i, including all variance caused by its interactions, of any order, with any other input variables.

2.2.2.1 Sobol indices

Sobol [SOB93] introduced the first order sensitivity index by decomposing the model function into summands of increasing dimensionality:

$$f(x_1 \dots, x_k) = f_0 + \sum_{i=1}^{k} f_i(x_i) + \sum_{i=1}^{k} \sum_{j=i+1}^{k} f_{i,j}(x_i, x_j) + \dots + f_{1,\dots,k}(x_1, \dots, x_k)$$

Formula 17: Decomposition of model function by Sobol. [SOB05]

This representation of the model function f(X), which is decomposed into summands of increasing dimensionality, holds if f_0 is the expectation of the output (constant) and the integrals of every summand over any of its own variables are zero. As a consequence of this, all the summands are orthogonal. [EIK05]

$$\int_0^1 f_{is}(x_{i1}, \dots, x_{is}) dX_{i,k} = 0 \quad if\ 1 \leq k \leq s$$

Formula 18: Decomposition into summands. [SOB93]

For Sobol indices, the total variance V(Y) is defined by:

$$V(Y) = \int_{\Omega^k} f^2(X)\,dx - f_0^2$$

Formula 19: Total variance in Sobol. [EIK05]

Also, it can define the partial variances like:

$$V_{i1\dots is} = \int_0^1 \dots \int_0^1 f_{i1\dots is}^2((x_{i1}, \dots, x_{is})dX_{i1} \dots dX_{is}$$

Formula 20: Partial variances. [EIK05]

Where $1 \leq i_1 < \dots < i_s \leq k$ and s=1… k

The Sobol indices are defined by:

$$S_{i1\dots is} = \frac{V_{i1\dots is}}{V(Y)}$$

Formula 21: Sobol indices. [EIK05]

2.2.2.2 Fourier Amplitude Sensitivity Test

Fourier Amplitude Sensitivity Test (FAST) method allows the computation of that fraction of the variance of a function which is due to each input. [SAL98]

FAST is a procedure that provides a way to estimate the expected value and the variance of the output variable and the individual contribution of input factors in the variance, basically through a search curve which tracks all entries space.

The sensitivity value is defined based on conditional variances which indicate the individual of the uncertain inputs on the output.

The main idea of FAST is transform the k-dimensional integral in x into a one-dimensional integral in s by using the transformation function [SAL99]

$$x_i = G_i \cdot (\sin(\omega_i s)) \quad for\ i = 1 \dots n$$

Formula 22: Transformation function. [SAL99]

Then, now, we can write the expectation of Y like:

$$E(Y) = \frac{1}{2\pi} \int_{-\pi}^{\pi} f(s) ds$$

Formula 23: Expectation of Y. [EIK05]

Where: $f(s) = f(G_1(sin(\omega_1 s)) \dots G_k(sin(\omega_k s)))$

Using Fourier properties, we can obtain an approximation of the variance of Y as:

$$Var(Y) = \frac{1}{2\pi} \int_{-\pi}^{\pi} f^2(s) ds - [E(Y)]^2 \approx \sum_{j=-\infty}^{\infty} \left(A_j^2 + B_j^2\right) - \left(A_0^2 + B_0^2\right) \approx 2 \sum_{j=1}^{\infty} \left(A_j^2 + B_j^2\right)$$

Formula 24: Variance of Y. [EIK05]

Where A_j and B_j are Fourier coefficients which are defined by:

$$A_j = \frac{1}{2\pi} \int_{-\pi}^{\pi} f(s) \cos(js) ds \qquad\qquad B_j = \frac{1}{2\pi} \int_{-\pi}^{\pi} f(s) \sin(js) ds$$

Formula 25: Fourier coefficients. [EIK05]

The contribution of X_i in the total variance of Y can be approximate, for a minimum sample size $N_s=2M\omega_{max}+1$, by:

$$D_{\omega i} \approx \sum_{p=1}^{\infty} (A_{p\omega i}^2 + B_{p\omega i}^2)$$

Formula 26: Individual variance. [SAL98]

And in the case, the global sensitivity index is:

$$S_i = \frac{2\sum_{p=1}^{\infty}(A_{p\omega i}^2 + B_{p\omega i}^2)}{2\sum_{j=1}^{\infty}(A_j^2 + B_j^2)} = \frac{D_{\omega i}}{D_{FAST}}$$

Formula 27: Global sensitivity index in FAST. [SAL98]

It is remarkable that Cukier, Koda and Saltelli, developed different transformation functions, G_i. These functions are the following [SAL99]:

Cukier→ $x_i = \bar{x}_i \cdot e^{\bar{v}_i \sin(\omega_i s)}$

Koda→$x_i = x_i(1 + \bar{v}_i \sin(\omega_i s)$

Saltelli→ $x_i = \frac{1}{2} + \frac{1}{\pi} sin^{-1}(\sin(\omega_i s))$

It is remarkable that the sample points usually are more uniformly distributed in the unit square using Saltelli transformation [SAL99].

2.2.2.3 Extended Fourier Amplitude Sensitivity Test

Saltelli proposed an improvement of FAST method to estimate the total effect indices like in Sobol indices. This method is called Extended Fourier Amplitude Sensitivity Test.

In EFAST we can calculate the total effect by estimating the variance in the complementary set V_{ci}^{FAST}, defined by: [EIK05] [SAL99]

$$\hat{V}_{ci}^{FAST} = 2\sum_{p=1}^{M}(A_{p\omega_{\sim i}^2} + B_{p\omega_{\sim i}^2})$$

Formula 28: Variance in the complementary set. [EIK05]

Also, it is necessary introduce a more flexible sampling scheme through a random phase-shift added into the transformation function.

$$X_i(s) = G_i(\sin(\omega_i s)) = \frac{1}{2} + \frac{1}{\pi}\arcsin(\sin(\omega_i s + \varphi_i))$$

Formula 29: Saltelli transformation function in EFAST. [EIK05]

Due to symmetry properties the curve now can be sampled over (-π, π). It is remarkable that the computational cost to obtain all first and total order indices are: $k(2M\omega_{max}+1)N_r$ where N_r is the number of samples that was done.

2.2.3 Computation of Sensitivity analysis

Sobol indices and EFAST are useful variance-based methods to identify the most important parameters, and in the last chapter it is possible to observe all formula which Sobol and Saltelli, respectively, developed.

Now a vision of how to compute the S_i, for EFAST method developed by [EIK05], is given in the following figure.

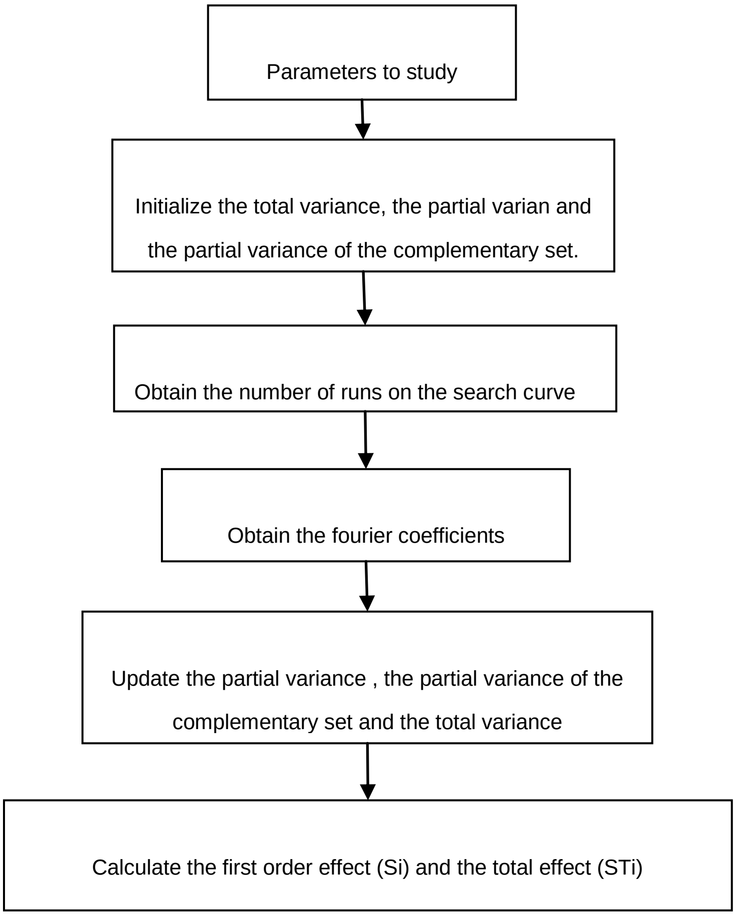

Figure 12: Computation of EFAST indices

2.3 Creation of networks

It is considered all possible network structures and supply tasks result in a large amount of possible networks. A consideration of all possible network is not effective because of the use of a variable local power transformer is only for a certain subset of these networks not for all. [SEE13]

In connection with the goal of the network, are particularly interesting the networks where VRDT can lead to an increase in the Integration Potential. According to the literature [KER10], rural and suburban networks are not able to integrate full potential of photovoltaic systems.

For this reason, radial networks are considered appropriate for rural and suburban supply. Also it is assumed that in these networks, exclusively, photovoltaic systems will be integrated, as these decentralized energy conversion systems are, in reality, the most relevant systems**.**

2.3.1 Modeling of radial networks

The model which was developed [SEE13] includes an algorithm to create a low voltage networks. These nets are calculated with MATPOWER a freely available tool for power flow calculation in MATLAB. A network model must satisfy certain conventions which are related to the structure and the included components, i.e, the restriction on nodes and edges [MAT11].

In this work, the nodes and edges allowed are divided in two species: linking nodes or cable distribution box where load node, for example a household, are connected. The connection between nodes is ensured by edges which represent the electrical lines. An edge between node and link load node is configured as a service line. Finally, the connection to medium voltage network with two nodes and an edge represents the transformer modeled. Basically, the link node can be a multiple occupancy load node, and a meshed networks. However there are, only in the following radial networks, a simple-occupancy nodes.

In figure (6) it can be observed the structure of an example network that was created using the grid generator. [SEE13]

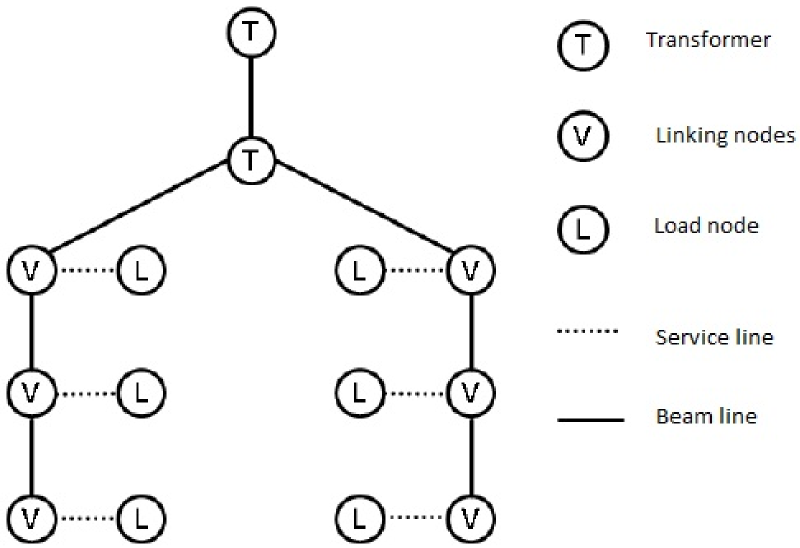

Figure 13: Construction of a network model. [SEE13]

The distance between the connection node and the length of service lines is simplified, assuming it is homogeneous, to reduce the number of required information in the created network. Furthermore, the service line types do not differ from each other, since preliminary studies have demonstrated that does not effect on the integration potential. Therefore, for all service lines are adopted the type NAVY 4x50 mm² and a cable length of 15 meters. Neglecting the service line is not possible, because it is relevant to the review of protection against indirect contact.

2.3.2 Input data and transformation

Once the basic structure of the networks was presented, now an explanation of the input data and, if it is necessary the respective transformation functions which can be used, are given. Over all, the input data consist of the following parameters: [SEE13]

- Length of the radiation power
- Number of departures from the local substation (radiating number)
- Apparent power of the transformer (transformer type)
- Distance of the connection node

- Line type of grid
- Penetration of load types:
  - Single-family homes
  - Small apartment buildings
  - Farms
- Load application factor
- Inhomogeneity factor

Every parameter is transformed into an appropriate structure for the network property and the sampling process takes a value between 0 to 1. Basically the input parameters, according to their range of values in discrete and continuous parameters, can be divided in the limit values.

For continuous parameters with limits like the jet length and the distance of the connection node, the transformation is performed by a linear interpolation. We can see in figure (7) that we define f(0)=min and f(1)=max

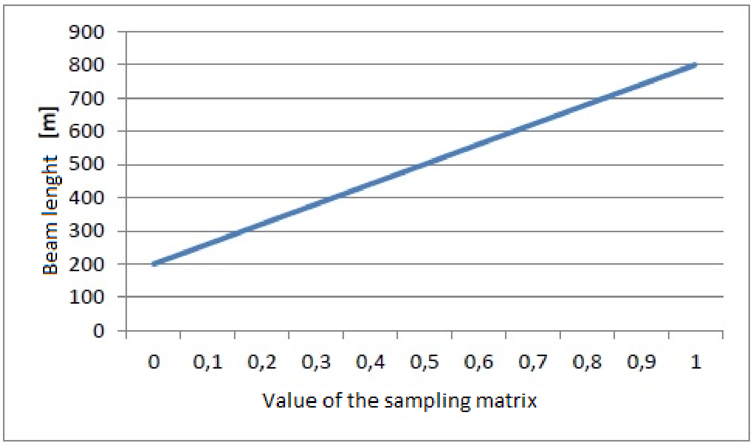

Figure 14: Interpolation for continuous parameters. [SEE13]

For parameters with a discrete range of values, the range between 0 to 1 is divided into equal amounts. The number of subsets is given by the number of possible values of the parameter, for instance the number of wire types. Taking the sampling procedure for the wire types, for example, a number between 0 and 1/6, the grid generator uses the first line types for the network beams.

Finally there are continuous parameters which are defined over the entire range between 0 to 1, with restrictions arising from the reality and the selected network model. In this cases, other approaches to transformation are necessary.

The transformation of these special parameters has disadvantages in terms of calculating the sensitivity indices, which result from the existence of strong dependencies in the model and can lead to distortions.

Nevertheless the cosen form of sensitivity analysis allows also knowledge about the qualitative ranking of input parameters, if dependencies exist with each other, it is simply impossible to determine quantitative effects. For this reason, parameters are also included in the model when it is clear by forecasting that dependencies exist between them. The qualitative ranking of the input data according to their "importance" is used in this work in the foreground.

Penetration of the load types → Due to the restriction to simple assignment of the connection node, the sum of the individual load type penetrations must be equal to 100%. For this reason, the solid value for single-family houses is retained and split the difference to 100% according to the values drawn between small multi-family houses and farms proportionately. In this way, distributions as shown in Figure (8). [SEE13]

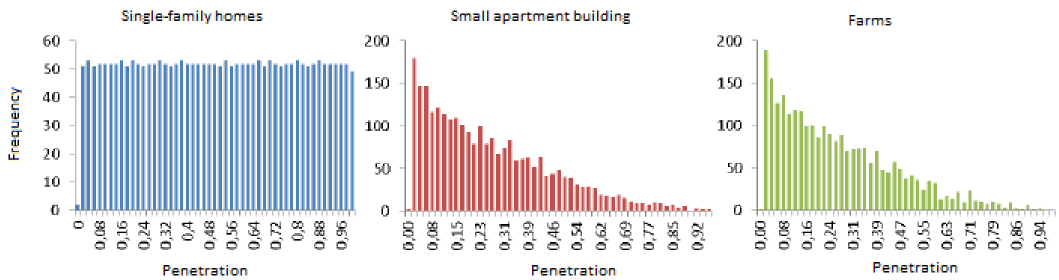

Figure 15: Distribution of the load-penetration after transformation. [SEE13]

Load application factor → The distribution of loads on a power beam leads assuming the same current at a certain voltage profile, which can be simulated by a dummy load to a specific location. The location of the equivalent load is determined by the calculation rule shown in Formula 16. [SEE13]

$$\varepsilon = \frac{1}{n \cdot l_{ges}} \sum_{i=1}^{n} l_i$$

Formula 30: Load application factor. [SEE13]

The load application factor must not determine by the grid generator, but resolved into individual nodes. The procedure was slightly adapted in this work assuming no load on the end of the power beam. nstead, all loads are combined in a package with very small house connection intervals (5 meters) and determined a minimum or maximum value for the load application factor. The actual load application factor then prescribes the distance of the load packet from the local substation, which is determined according to the formula 17. [SEE13]

$$l_1 = \frac{1}{n} \cdot (\varepsilon_{soll} \cdot n \cdot l_{ges} - \sum_{i=2}^{n} l_i)$$

Formula 31: Calculation of the approach point. [SEE13]

In this way the information about the true distribution of loads is lost in a network, but at the same time gaining the model parameters for a systematic set the location of consumers and distributed generation, which can be examined using sensitivity analysis. The information gained by this simplification is considered in comparison with the loss of information on the distribution of nodes as valuable.

Inhomogeneity factor (IHF)→ By the procedure described, so far, it was created the grid generator low voltage grids with a certain number of equal length beam power, which is an oversimplification of actual networks. For this reason, a parameter called Inhomogeneity factor is introduced. This leads to the creation of networks with different length beams. The factor is defined such that a value of 1 corresponds to a maximum inhomogeneous network, so very different beam lengths, while a factor of 0 corresponds to a network with homogeneous beam lengths to ensure that all possible cases are covered. For this factor, dependencies arise from the model, as a network beam shall not be less than the maximum distance between the tie knot, which would lead to a net beam without consumers. Therefore the Inhomogeneity factor is defined depending on the drawn jet length and the length of the shortest beam in a grid of Formula 18. [SEE13]

$$l_{min} = \frac{1}{1 + 3 \cdot IHF} \cdot l_{max}$$

Formula 32: Determination of the minimum beam length with Inhomogeneity factor (IHF). [SEE13]

The prefactor of Inhomogeneity factor results from the ratio between the shortest beam length and maximum distance of the link nodes minus one. With this calculation rule of the shortest beam power shall in no case to a value less than 50 meters

To calculate the other beam lengths, a linear function in the way it is determined that the first beam, the drawn length l_{max}, the last beam has calculated the Inhomogeneity length l_{min} and possible beam lengths are in between are linearly interpolated.

3 Modelling

In this section the methodology used to develop and obtain the first order and total effect by using Extended Fourier Amplitude Sensitivity Test, are presented.

3.1 Goal and application of Sensitivity analysis

The main goal of this thesis is to obtain the most important parameters in the network by using a mathematical approach. Obtaining the most important, the most relevant parameter of the network, it is possible to change its value to try to optimize the integration potential and, therefore, increase the PV installed in the network which is one important goal to obtain more and more renewable energies installed in the system.

As it is mentioned in the chapter 2.2, there are different methods to study the first and total order but in this case, a variance based method are used. The most important variance based methods are Sobol indices and Fourier Amplitude Sensitivity Test (FAST). Extended Fourier Amplitude Sensitivity Test (EFAST), which is an improvement of FAST that allows calculate the first order effect and the total effect of the parameters, are used. It is remarkable that with FAST, it is possible to obtain only the first order effect.

EFAST solves problems where non-linear and non-monotonic data are used and it can be considered as truly quantitative for global Sensitivity Analysis for numerical experiments. This means that EFAST can rank different parameter of a real model in order of their relative importance.

It should take into account that, in average, EFAST yields better estimates than Sobol and in terms of robustness, EFAST is also better, it converges faster to the analytical values, even at low sample sizes, than Sobol indices. [SAL97]

Finally, after the sensitivity analysis, also the integration potential of the network following the steps described in chapter 2.1.3 and 2.1.4 are calculated.

3.2 Implementation

In this section, the procedure to create the different grids and to evaluate the most influential parameters is explained. For this purpose, three MATLAB's codes are used. The first code is „EFAST_Analyse.m" (see the code in Appendix A) where the different networks following the characteristics of EFAST process are created. Later, „Versuchsdurchfuehrung.m" is used to simulate and obtain the values of the network like PV for each node and total, integration, the kind of node (PV, PQ), and the maximum and minimum voltage. Finally with these values, „EFAST_Austwertung.m" (see the code in Appendix B) are used to obtain the first order and the total effect as well as the integration potential as was described in the chapter 2.

The development of „EFAST_Analyse.m" and „EFAST_Auswertung.m" are explained in depth

It is remarkable that for the creation of EFAST codes, the steps which are presented in „Eikos. A simulation Toolbox for Sensitivity analysis" [EIK05] are followed but adapting to our case, making different changes like the number of runs on each curve or the transformation of data in the creation of random inputs.

Firstly in „EFAST_Analyse.m", random networks, where the size of the samples depends on the parameter WantedN, are created. It can change easily WantedN to increase or decrease the number of samples. For example, in the chapter 4 about Results, there are results for different samples sizes, namely, sizes of sample 1000, 5000, 7500, 10000, 12500, 15000.

The first step is to define the different parameters and their bandwidths. Later, the random values of input for each parameter are created. As it is mentioned in the chapter 2.3.2 there are 10 inputs parameter:

- Length of the radiation power
- Number of departures from the local substation
- Apparent power of the transformer
- Distance of the link node
- Line type.
- Penetration of load types:
    - Single-family homes (SFH)

- Small apartment buildings (SAP)
- Farms

* Load application factor
* Inhomogeneity factor

For the creation of these random values, it is necessary the Saltelli’s Transformation:

$$X_i(s) = G_i(\sin(\omega_i s)) = \frac{1}{2} + \frac{1}{\pi}\arcsin(\sin(\omega_i s + \varphi_i))$$

Formula 33: Saltelli transformation function in EFAST. [EIK05]

After obtaining these inputs, a transformation using a linear interpolation is performed. These transformations are divided into three parts: discrete data, not discrete data and for penetration data.

Finally, it is deleted the invalid networks that had been created, and it is saved the data in different folders according to each parameter in the „Berechnungsfaelle" folder.

Secondly, it is used „Versuchsdurchfuehrung" to obtain valid results for the samples that are created by using of „EFAST_Analyse.m“. This code give us, in a structure, different parameters for each sample of the network like: Integration, PV total, voltage and so on.

Last but not least, it is done the analysis of the results, which usually are stored on the folder called „Ergebnisse" through „EFAST_Austwertung.m". Firstly it is necessary to load the results which are obtained with „Versuchsdurchfuehrung". It is deleted the invalid results and It is assigned the result vectors.

It is remarkable the importance of the variable „fillwithzeros“. With this variable it is possible to choose between fill with zeros the networks which are invalid or not fill, depends on the value (true or false) of the variable. It is relevant to take into account the invalid network because without „fillwithzeros“ this networks disappear from the study and, it is obvious that this networks also influence in the system while with „fillwithzeros“, this invalid networks are considered as null.

For the determination of the effects, the steps from „Eikos A simulation Toolbox for Sensitivity analysis" are followed [EIK05] to obtain the values of the coefficients of Fourier.

$$A_j = \frac{1}{2\pi}\int_{-\pi}^{\pi} f(s)\cos(js)\,ds \qquad B_j = \frac{1}{2\pi}\int_{-\pi}^{\pi} f(s)\sin(js)\,ds$$

Formula 34: Fourier coefficients. [EIK05]

Later, the partial and total variance, the EFAST indices which represent the first order effect, the total effect and the integration potential of each parameter are obtained. Recall their expressions.

$$D_{\omega i} \approx \sum_{p=1}^{\infty}(A_{p\omega i}^2 + B_{p\omega i}^2)$$

Formula 35: Individual variance. [SAL98]

The main outputs which were obtained for each kind of sample sizes, are: the first order indices (EFAST indices for each parameter), the total effect, the partial variance of each parameter, the variance of the complementary group and the total variance.

In the next chapter, the obtained results by using this methodology are provided.

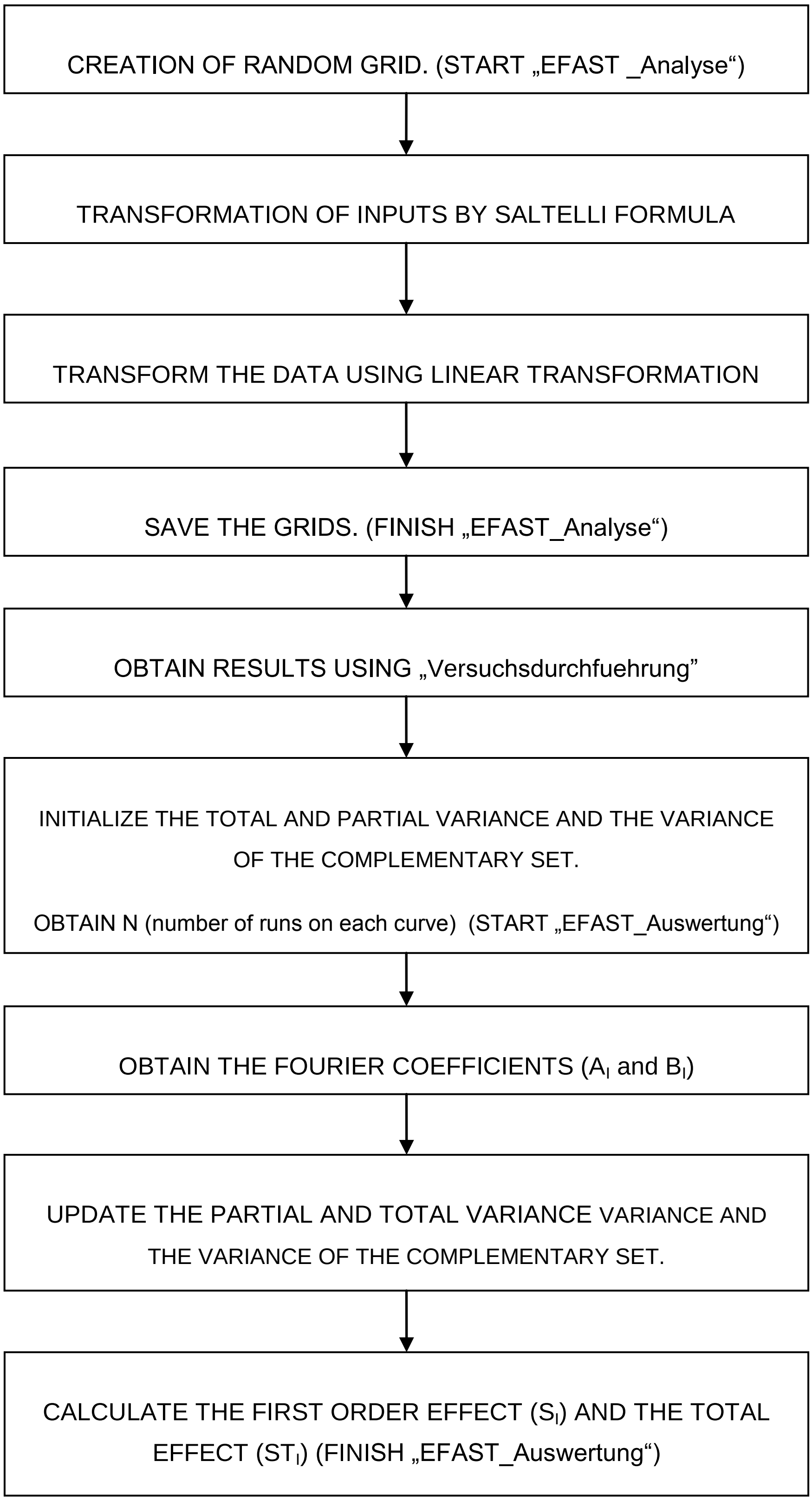

Figure 16: Flow chart of EFAST method

4 Simulation and Results

In this section it is presented the results that are obtained from the application of the method explained in the section 3.2. To remember, first it is created a network through „EFAST_Analyse.m“, secondly it is made simulations for every network which was created in the first step, with the program „Versuchsdurchfuehrung.m". And finally, it is obtained the sensitivity indices and the most relevant parameter in the network by using „EFAST_Austwertung.m“

4.1 Sensitivity indices

First of all, the results for different simulations with different sample sizes are presented. The sample sizes are: 1000, 5000, 7500, 10000, 12500, 15000.

It is used different number of sample to compare the operation of the EFAST method for different number of samples sizes, to know if the method is reliable in smaller samples.

The main outputs which were obtained for each kind of sample sizes, are: the first order indices (EFAST indices), the total effect, the values of integration potential, the partial variance, the variance of the complementary group and the total variance, respectively for each parameter. It is possible to see all values in the tables from the Appendix C.

The first order effect with and without filling zeros, for the different sample sizes, are presented in the next graphics.

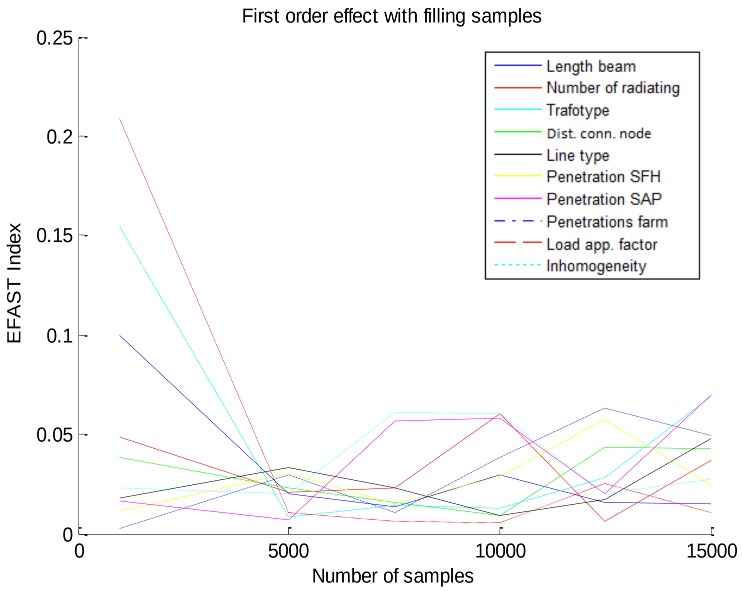

Figure 17: First order effect with filling zeros by using EFAST

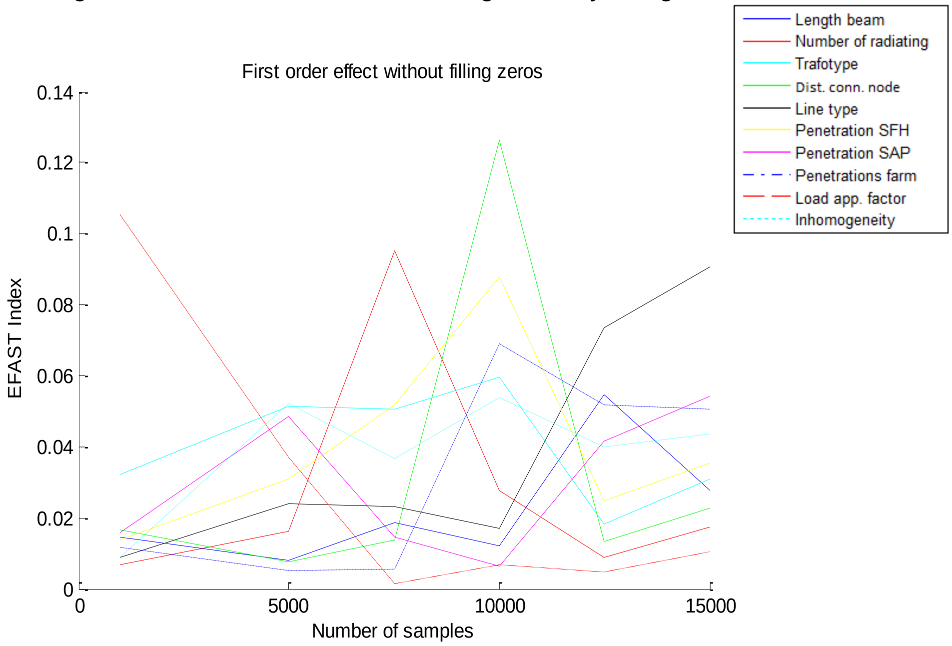

Figure 18: First order effect without filling zeros by using EFAST

At the view of the graphics it is remarkable that in both cases for cases with a lower number of samples sizes, the most relevant parameter is the number of radiating. Increasing the number of samples the penetration take more relevance in both case. It is remarkable that for the biggest sample, in the case of without filling zeros instead of invalid networks, the most important parameter is the line type, but for filling zeros instead of invalid networks the penetration buildings is the most relevant parameter.

It makes more sense the results obtained with filling zeros instead of invalid networks because it is clear that the penetration should be considered too important to improve the HC.

In both cases it is remarkable that the results do not give results as expected. In the next section, EFAST method and Sobol indices which was developed by Stefan Seeman, are compared

4.2 Comparison with Sobol indices

In this section the results obtained by using EFAST and Sobol method developed by Stefan Seeman [SEE13] are compared. Also it is discussed about the validation of the results obtained in EFAST which are presented in the chapter 4.1.

In the following figure it is possiible to observe the first order indices, with filling zeros instead of invalid networks, for different number of samples sizes. It is remarkable that in EFAST, the values are obtained for a concrete number of samples, then the graphics have a linear trend between the different number of sizes.

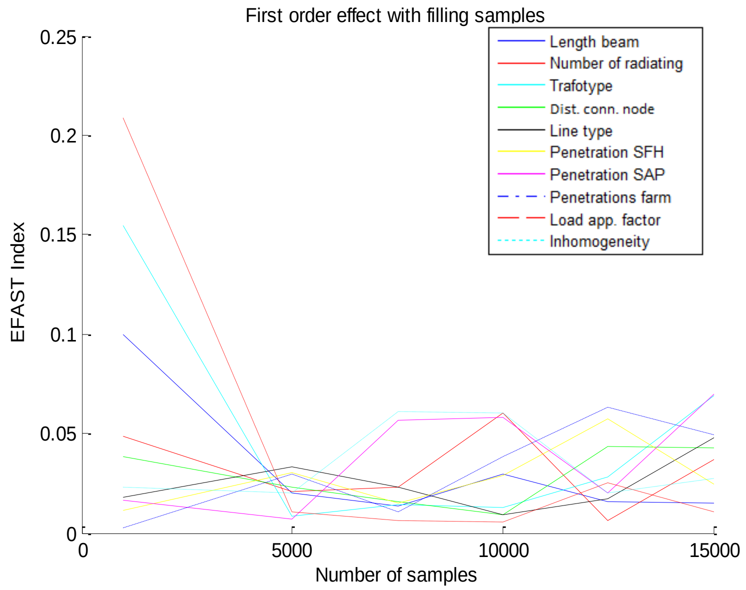

Figure 19: First order effect with filling zeros by using EFAST

In the following figure, the first order indices, without filling zeros instead of invalid networks, for different number of samples sizes are presented.

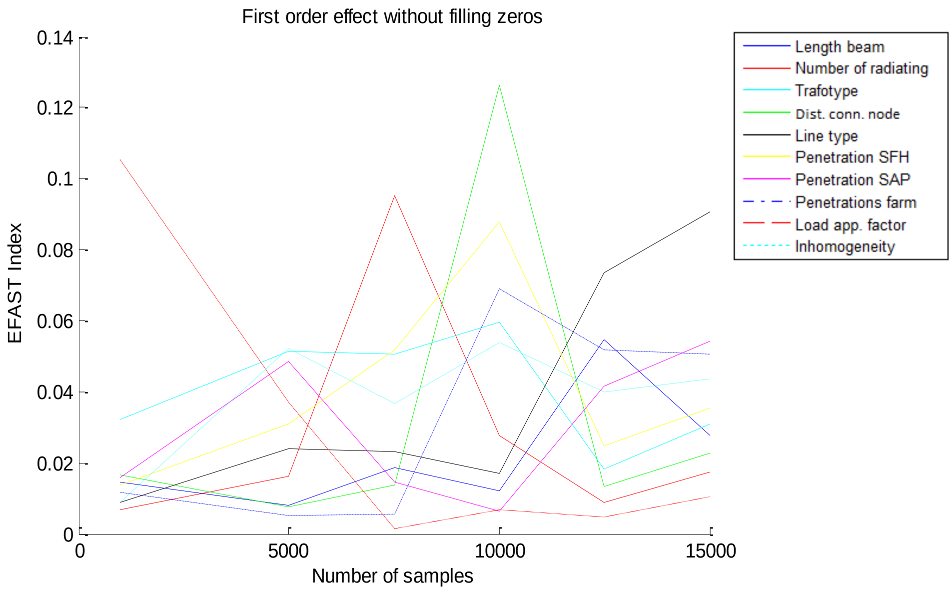

Figure 20: First order effect without filling zeros by using EFAST

Seeing the graphics, it is obvious that the case with filling zeros is more exact than the case without filling zeros, because the trend of graphic and also the values take more sense than the case without filling zeros. It should be only for the reason that for EFAST,really, all networks are needed to obtain the best index for each parameter, and changing the invalid values to zeros, it is took into account all created grids obtaining more accuracy than without this change.

Stefan Seemann obtained the next plot for the first order effect by using Sobol indices. [SEE13]

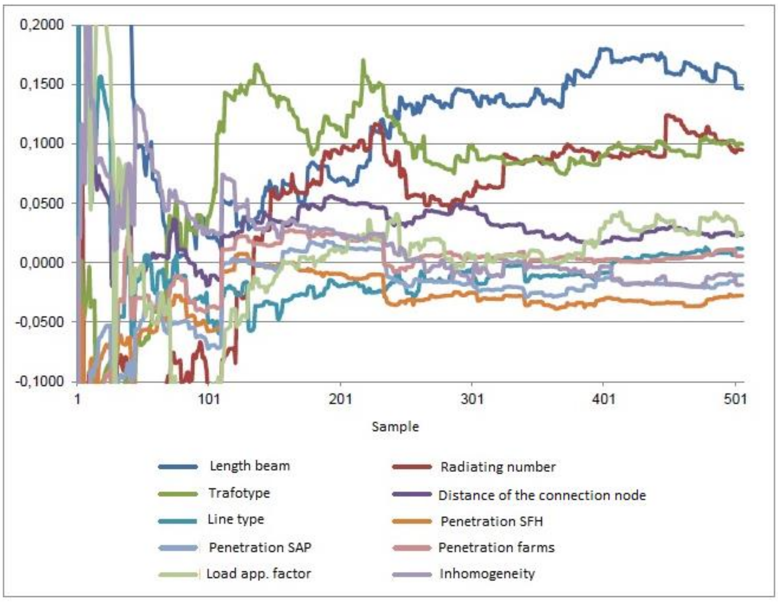

Figure 21: First order effect by using Sobol indices. [SEE13]

By comparison of the last graphs, it is obvious that the plots are too different, the trend and also the values are completely different. This means that probably there are failures in the model that it should be investigated in depth. In the section 4.3, different possibilities for the sources of error are given.

Also it is possible to compare the convergence values for each parameter both in EFAST and in Sobol.

In the next graphics it is obtained the convergence values from each parameter.

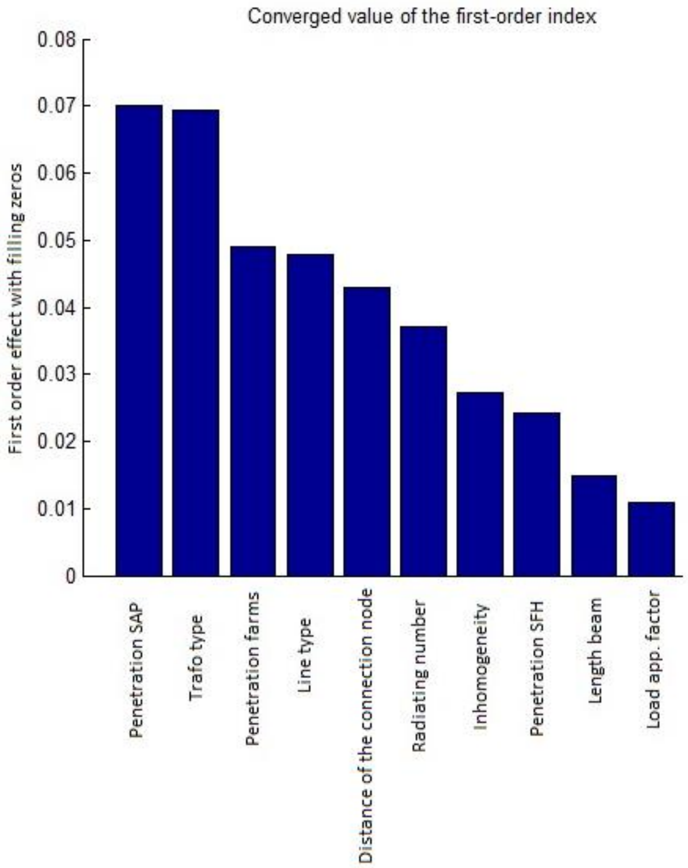

Figure 22: Converged values of the first order index for EFAST with filling zeros

Following the last graphics, the most important parameter using EFAST with filling zeros instead invalid networks are: penetration of small apartment buildings,the type of transformers, this is depending on the apparent power of the transformer, and the penetration of farms. It is clear that the penetration of the loads are too important in a network and in this case EFAST proves it.

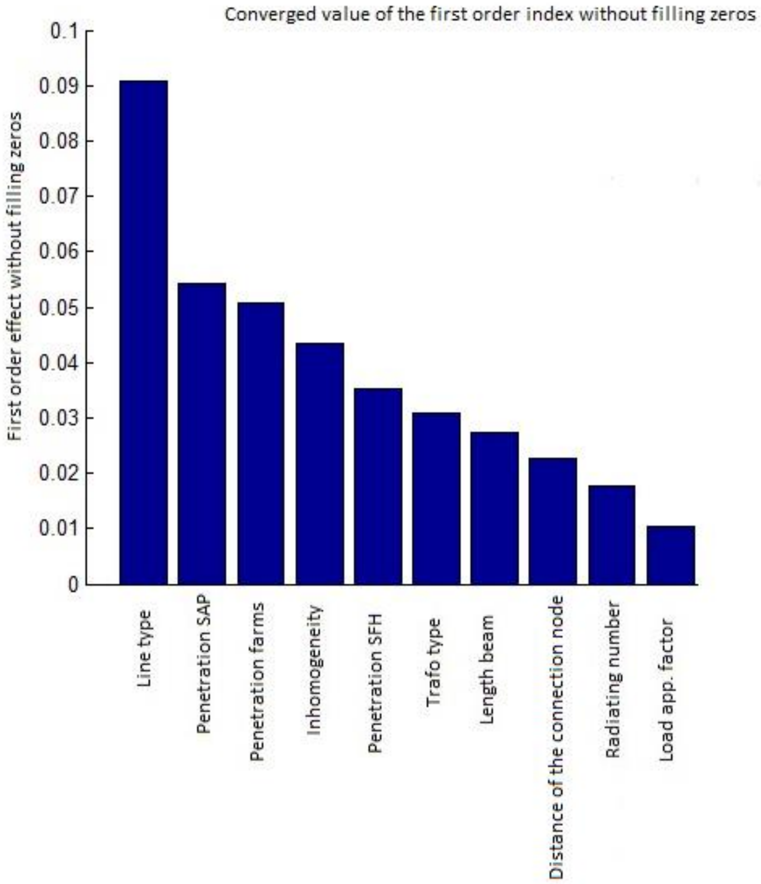

Figure 23: Converged value of the first order index for EFAST without filling zeros

In the case of EFAST without filling zeros, the most important parameter are line type, penetration of small apartment buildings and penetration of farms. It is remarkable that the only parameter which changes, is line type which is the parameter with the highest convergence value of the first order effect (0,09).

The converged values for the first order effect obtained by using of Sobol indices are presented in the next graph.[SEE13]

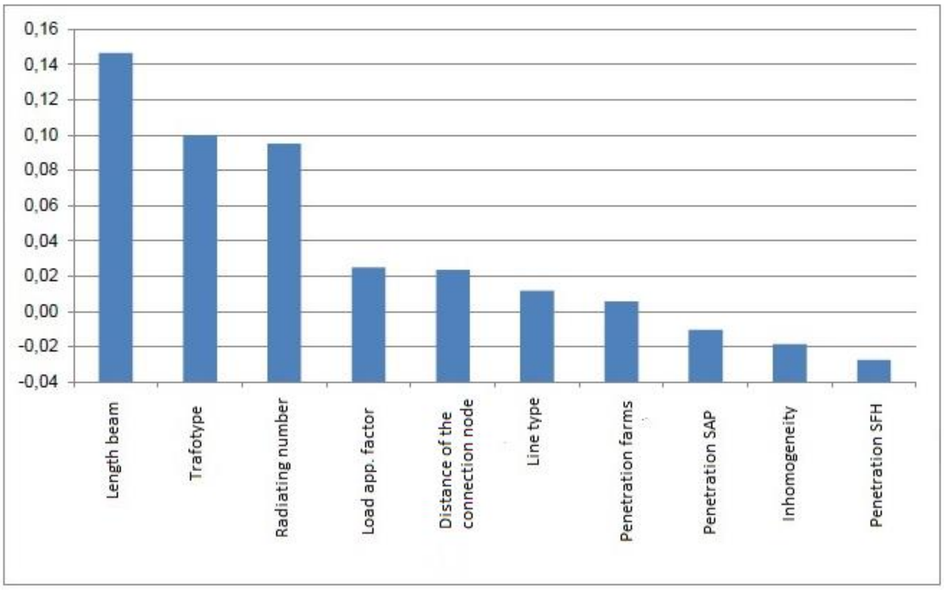

Figure 24: Converged values of first order effect for Sobol indices. [SEE13]

In this case the most relevant parameters are: length beam, transformer type and the radiating number, this is the number of departures from the local substation. As it is mentioned in the last section, the difference between Sobol indices and EFAST may be because of the presence of failures in the model.

Now the graphics for the total effect, also with filling zeros instead invalid networks and without, and the obtained graph for the Sobol indices are compared.

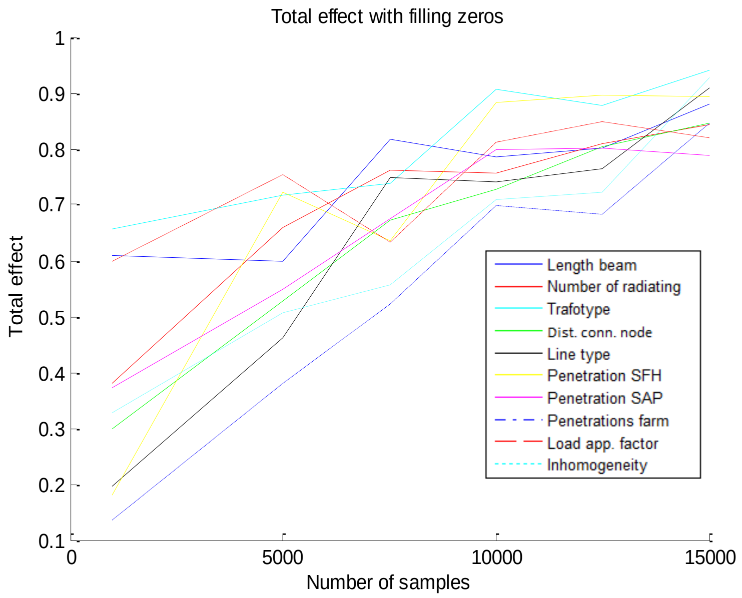

Figure 25: Total effect by using EFAST with filling zeros

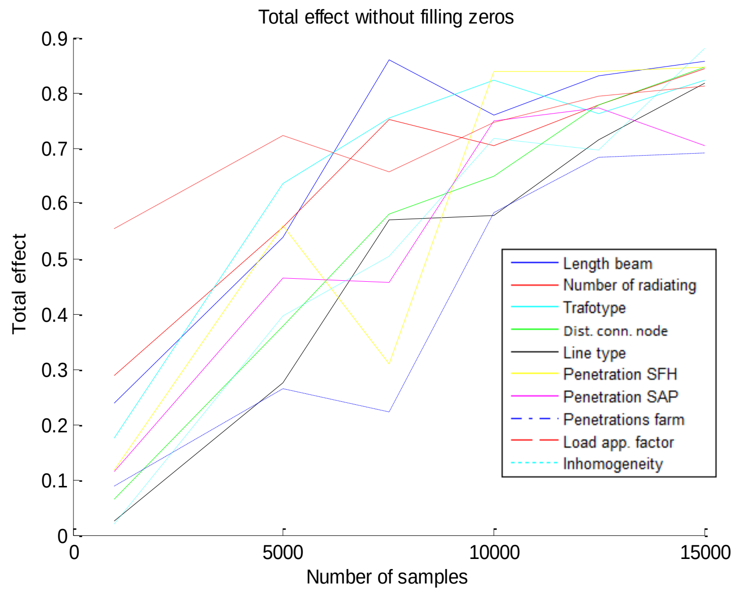

Figure 26: Total effect by using EFAST without filling zeros

It is clear, in both cases the total effect increase with the number of samples for each parameter. This is normal because as the first order effect decreases with the number of samples, and the first order effect and the total effect are directly related.

Stefan Seemann obtained the next plot for the total effect by using Sobol indices. [SEE13]

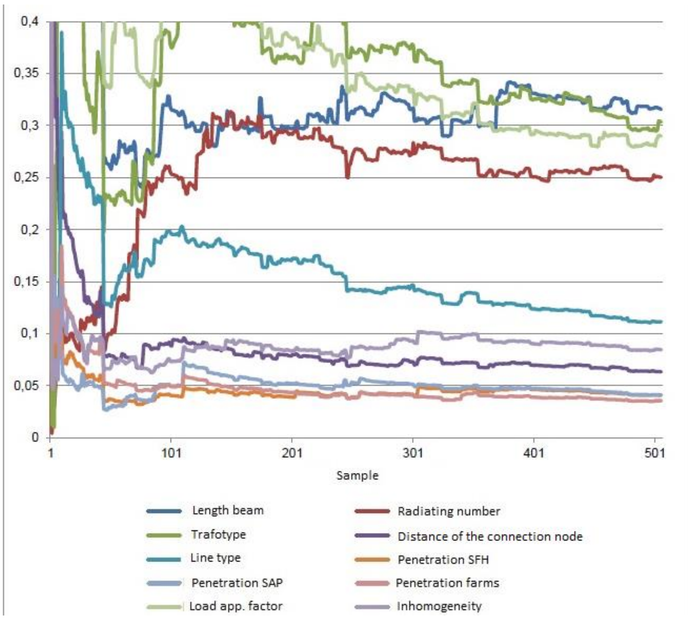

Figure 27: Total effect for Sobol Indices. [SEE13]

It is remarkable that the converged values of the total effect are lower in Sobol indices than in the EFAST methods, but as it is commented before it may be because of the presence of failures in the model.

The big differences between EFAST and Sobol method, show that EFAST do not work in the correct way and therefore it is impossible to predict correctly which parameters are the most important in the model. In the next section a different sources of error which can produce the failures in the process, are given

4.3 Sources of error

As it is mentioned in the last section, the results are not satisfactory as they should be. Therefore in this section, a possible sources of error that may happen in the method are presented.

- **Number of samples→**it is clear that in Sobol and EFAST, it is not obtained the same graphics, even the graphs do not have the same trend. Maybe the fact of using the Matlab's function „Sobolset" is an important difference between methods, because with „Sobolset", samples for each point in the network are created and the graphics that are obtained can be continuous.

- **Mathematical source→** EFAST uses derivatives and integrals (infinitesimal calculations of a function) to find the data on the distribution associated with each input factor, and for the discrete case, EFAST searches finite spaces. This approach brings about that the method can be unreliable.

- **Number of inputs→** It is important to know that when EFAST is applied to models with many input parameters, the noise level is high compared to the others variance-based methods like Sobol or Jansen. This explains that other parameters (without relevance) can increase the uncertainty in the system because of the presence of interference in the sampling scheme of EFAST. It should be further investigated.

- **Transformation of data**--> In Sobol it is clear that we need a linear transformation for the data. This kind of transformation are also used in EFAST (in concrete in „EFAST_Analyse"), but it should remember that EFAST uses Fourier coefficients, then our rank of work is between $-\pi$ to π, and in Sobol, between 0 to 1. Maybe it is necessary another type of transformation to set better our model and also to make more realistic.

  One of the possible solutions to the code could be find another transformation, another interpolation which is adjusted for sinusoidal values. It should deepen in Fourier analyse and their transformations.

4.4 Conclusion

At view of the obtained results it is clear that the EFAST method does not work in the correct way and it is impossible to predict which parameter is the most important in the model. It is true that the results taking into account the variable called "fillwithzeros" give us an idea of which parameters could be the most important in our model, but it is not possible to ensure.

In general variance-based method, and of course EFAST method, can help us a lot to decide what parameters it is possible to change to improve the system. It is important in order to analyse a model because by using a simulation of the network and a mathematical approach it is possible to obtain the most important sources of the model. It is really important to simplify the study because it allows us to focus on this parameters to improve all that it would be possible the PV obtained in our model.

Unfortunately EFAST does not work in the correct way but I think that with enough time, we can make that the method will work in order to simplify the model to analyse the network and its parameters. It can be interesting to use more time to try to solve the problems that appear in the code, focusing, above all, in the different sources of error which are given before.

5 Summary and Outlook.

5.1 Summary

In this document it talks about renewable energy, in special about photovoltaic systems. For the future of the world, renewable energies are too important because they are a major focus of obtaining alternative energy which help improve the levels of pollution of the planet as they do not cause any kind of pollution.

To this end, members of IFHT developed different methods to improve the Integration Potential in a network based on the german model.

Ainteresting method based on the sensitivity analysis are developed, specific in variance-based method, this is the Extended Fourier Amplitude Sensitivity Test to study the most relevant and important parameter for the network in order to improve the Integration Potential in the network, and therefore to can install more and more PV systems in the model.

For EFAST method, the task is divided into two Matlab's files, „EFAST_Analyse“ and „EFAST_Auswertung“.

In „EFAST_Analyse“, it is possible to create a random grids based on the model but with the mandatory specifications for EFAST method. In this network, there are ten different parameters, namely: length of the radiation power, number of departures from the local substation, apparent power of the transformer, distance to the link node, line type, penetration of load types which can be for single-family homes (SFH),small apartment buildings (SAP) or farms, load application factor and inhomogeneity factor.

It is remarkable that a linear interpolation is used to transform the input data, and also, for specifications of the method, it is used the Saltelli's transformation

$$X_i(s) = G_i(\sin(\omega_i s)) = \frac{1}{2} + \frac{1}{\pi}\arcsin(\sin(\omega_i s + \varphi_i))$$

Formula 36: Saltelli transformation function in EFAST. [EIK05]

Once it is created this grids for each parameter, it is made different simulations using „Versuchsdurchfuehrung.m“ . With the help of this tool belonging to IFHT, it is obtained values like PV for each node and total, integration, the kind of node (PV, PQ), the maximum and minimum voltage and so on.

In „EFAST_Austwertung“ it is possible to analyse the most important parameter in the model through the results obtained in „Versuchsdurchfuehrung.m“.

With the help of the analysis, it should be able to determine the most important parameters, studying the first order effect and the total effect for each parameter in the network, but as it is exposed in the chapter 4, there are failures which produce that the program does not work in the correct way by comparison with Sobol indices developed in a previous thesis.

5.2 Outlook

As it is shown in the last chapters, unfortunately our EFAST method does not work in the correct way.

In the section 4.3, different error sources are mentioned. It is important to discuss and study this ways to try to find and solve it the failures.

It should deepen in the field of the Fourier analyse and their transformations. In our EFAST method, a linear interpolation is used to transform the random data input and maybe, for using the Fourier coefficients this transformation is not valid.

Also it should studied how the number of inputs parameters affect to the noise in EFAST method, because as it is mentioned before, parameters (without relevance) can increase the uncertainty in the system because of the presence of interference in the sampling scheme of EFAST.

Therefore one of the goals it should be to work in this direction, to try to avoid possible failures and, above all, find a solution for the problem, because if EFAST works in a correct way is an useful tool.

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Abbreviations list

ANOVA	Analysis of Variance
DER	Distributed Energy Resources
DG	Distributed Generation
EFAST	Extended Fourier Amplitude Sensitivity Test
FAST	Fourier Amplitude Sensitivity Test
HC	Hosting Capacity
IFHT	Institut für Hochspannungstechnik an der RWTH Aachen
IHF	Inhomogeneity factor
IP	Integration Potential
kWp	kiloWatts peak
PV	Photovoltaic
RWTH	Rheinisch-Westfälische Technische Hochschule
SA	Sensitivity Analysis
VRDT	Voltage Regulated Distribution Transformer

Appendix A: EFAST_Analyse code

```
function [x_res,Wahre_Stichprobe, Aussortiert_res,k] =
EFAST_Analyse()

%EFAST_Analyse creates a sample based on our network to can %ob-
tain the most important parameter using Extended Fourier Ampli-
tude Sensitivity Test.

%We obtain a first order sensitivity indices (Si) and total %ef-
fectsensitivity indices (STi) using EFAST_Austwertung.

%-----------------------------------------------------------
%%INPUTS:
% wantedN: wanted number of sample points

%%OUTPUTS:
% x_res: cell array containing the x (see below) for every pa-
rameter
% Wahre_Stichprobe_res: vector containing the number of %samples
for each parameter after deleting invalid networks
% Aussortiert_res: lines of x that have been sorted out
% k: number of parameters

%%OTHER USED VARIABLES/ CONSTANTS
% OM[]: vector of k frequencies
% OMi: frequency for the group of interest
%OMCi[]: Set of frequencies used for the complete group
%X[]: Parameter combination rank matrix
%AC[] BC[]: Fourier coefficiets
%Fi[]: Random phase shift
%N: Number of runs on each curve
%----------------------------------------------------------------
-----


%% Loading the load profiles

global HH_JEB
global HH_Lasten_INT16
global Standardlastprofile

load('Standardlastprofile');
load('HH_Lasten_INT16');
load('HH_JEB');


Erstellt = 0;
Ordner_nr = 1;
trigger_Aufteilung= false;  %division_trigger: Breakdown of
%networks by creating folders with 'NetworksPerFolder' each
```

```
NetworksPerFolder = 50;
trigger_Speichern = true; %Save true
Aussortiert=[];

%% Define parameters and bandwidths

Daten.Laenge_Strahl = [0.2; 0.8];%1 Length of beam
Daten.Anzahl_Strahl = [2 3 4 5 6 7 8];%2 Number of radiating
Daten.Trafotypen = [32 33 34 35]; %3 Transformer types
Daten.Abstand_HA = [0.015; 0.05]; %4 Distance node link
Daten.Leitungstypen = [55 56 57 58 59 705]; %5 Line types
Daten.Durchdringung_EFH = []; %6 Penetration single-family homes
Daten.Durchdringung_KMFH = []; %7 Penetration Small apartment
buildings
Daten.Durchdringung_L0 = [];%8 Penetration farms
Daten.Ortsparameter = []; %9 Location parameters (Load applica-
tion factor)
Daten.Inhomogenitaet = [];%10 Inhomogeneity

Name_Daten = fieldnames(Daten);


%Developing EFAST like in EIKOS
Nr=1; %Number of runs on each curve
%We obtain the size of the sample which we need to develop %the
EFAST code (EIKOS)
MF= 4; %MF is the maximum number of Fourier coefficients %that
may be retained in calculating partial variances %without inter-
ferences between the assigned frequencies.

k = size(fieldnames(Daten),1); %Our number of parameters
Name_Daten = fieldnames(Daten);

%wantedN is  the wanted number of sample points. We'll give %the
value of the size sample that we'll want to study
wantedN=30000;

%Computation of the frequency for the group of interest 'OMi'
and the number of sample points 'N'.
OMi=floor((wantedN/Nr-1)/(2*MF)/k);
N=2*MF*OMi+1; %Number of runs on each curve

if(N*Nr<65)
    fprintf('Error: sample size must be >=65 per factor.\n');
    return;
end

%Algorithm for selecting the set of frequencies.
%OMCi(i), i=1:k-1, contains the set of frequecies to be %used by
the complementary group.
OMCi=setfreq(k-1,OMi/2/MF);
```

```
for i1=1:k %Same analysis once for every parameter in EFAST
    %Loop over the 'Nr' search curves
    for L=1:Nr
        %Setting the vector of frequencies 'OM' for the 'k'
factors.
        cj=1;

        for j=1:k
            if(j==i1)
                %For the factor of interest
                OM(j)=OMi;
            else
                %For the complementary group
                OM(j)=OMCi(cj);
                cj=cj+1;
            end
        end
        %Setting the relation between the scalar variable %'S'
and the coordinates {[x(1), x(2),...x(k)]} of each %sample
point.
        Fi=rand(1,k)*2*pi; %Random phase shift
        S_vec=pi*(2*(1:N)-N-1)/N;
        OM_vec=OM(1:k);
        Fi_mat=Fi(ones(N,1),1:k)';
        angle=OM_vec'*S_vec+Fi_mat;
        x=0.5+asin(sin(angle'))/pi; %Saltelli transformation:
Xi=Gi*sin(omega(i)*s)

        %TRANSFORM DISTRIBUTIONS FROM STANDARD UNIFORM TO
GENERAL
        %x=distTransform(x);In eikos.

        %We transform the data using a linear transformation
like Stefan in Sobol_Analyse
        for i = 1:k
            if size(Daten.(Name_Daten{i}),1)>1  %Not discrete
data
                %Determine linear transformation function
                b = Daten.(Name_Daten{i})(1,1);
                m = Daten.(Name_Daten{i})(2,1) - b;

                x(:,i) = round((m*x(:,i)+b)*1000)/1000;

                %Ensure min value is not exceeded
                x(x(:,i)<Daten.(Name_Daten{i})(1,1),i) =
Daten.(Name_Daten{i})(1,1);

                %Values between 0 and 1
            elseif isempty(Daten.(Name_Daten{i}))
                x(:,i) = round(x(:,i)*1000)/1000;
```

```
            else % Discrete Data
                Anz_Parameter = size(Daten.(Name_Daten{i}),2);
                Vektor_indices = ceil(x(:,i)*Anz_Parameter);
                for l=1:size(Vektor_indices,1)
                    x(l,i) =
Daten.(Name_Daten{i})(Vektor_indices(l));
                end
            end

        end

        %Transform penetration of the load
        if isfield(Daten,'Durchdringung_EFH')
            for i2 = 1:size(x,1) %Auxiliar parameter
                x(i2,[7,8]) = [ x(i2,7)*(1-
x(i2,6))/(x(i2,7)+x(i2,8)) , x(i2,8)*(1-
x(i2,6))/(x(i2,7)+x(i2,8)) ];
            end
        end
    end

    % Create and store the networks for each parameter
    Ursprungspfad = cd;
    cd('Berechnungsfaelle');

    if trigger_Speichern
        OrdnerName = ['Netze_Parameter' num2str(i1), '_Ordner'
num2str(Ordner_nr)];
        mkdir(OrdnerName);
        oldFolder = cd(OrdnerName);
        Erstellt = 0;
    end
    Ungueltige_Netze = []; %For invalid networks
    Aussortiert = [];

    % % Create the networks
    for Nr_Stichprobe = 1:N
        [mpc, success] = Netzgenera-
tor_SOBOL(x(Nr_Stichprobe,:));
        if success == 0 % Planning criteria injured -> set %the
flag for deletion
            Ungueltige_Netze = [ Ungueltige_Netze;
Nr_Stichprobe];
            Aussortiert = [Aussortiert; x(Nr_Stichprobe,:)];

        else
            if Erstellt >= NetworksPerFolder &&
trigger_Aufteilung
                Erstellt=0;
                Ordner_nr=Ordner_nr+1;
```

```
                OrdnerName = ['Netze_Parameter' num2str(i1),
'_Ordner' num2str(Ordner_nr)];
                cd (oldFolder);
                mkdir(OrdnerName);
                oldFolder = cd(OrdnerName);
            end
            if trigger_Speichern
                save(['Netz_Sample_EFAST_Parameter' num2str(i1),
'_Stichprobe' num2str(Nr_Stichprobe)],'mpc');
                Erstellt = Erstellt + 1;
            end
        end
    end
    Wahre_Stichprobe = size(x,1);
    Wahre_Stichprobe = Wahre_Stichprobe -
size(Ungueltige_Netze,1);%true_sample
    Wahre_Stichprobe_res(i1) = Wahre_Stichprobe;
    x(Ungueltige_Netze(:,1),:)=[];
    x_res{i1} = x;
    Aussortiert_res{i1} = Aussortiert;

    cd(Ursprungspfad)
end
cd(Ursprungspfad);
%Algorithm for selection of a frequency set for the complemen-
tary group.
%Done recursively as described in [Saltelli]
    function OMCi=setfreq(Kci,OMCiMax)
        if Kci==1
            OMCi=1;
        elseif OMCiMax==1
            OMCi=ones(1,Kci);
        else
            if (OMCiMax<Kci)
                infd=OMCiMax;
            else
                infd=Kci;
            end
            istep=round((OMCiMax-1)/(infd-1));
            if (OMCiMax==1)
                istep=0;
            end
            otmp=1:istep:infd*istep;
            f1_infd=floor(infd);
            for g=1:Kci
                n=mod(g-1,f1_infd)+1;
                OMCi(g)=otmp(n);
            end
        end
    end
 end
```

Appendix B: EFAST_Austwertung code

```
function [ Daten ] = EFAST_Auswertung( Pfad, k )

%EFAST_Auswertung gives us the first order sensitivity analysis
and the total effect by using the Extended Fourier Amplitude
Sensitivity Test.First, it is necessary to run %EFAST_Analyse.

%Outputs
%Daten.EFAST_Indices--> First order effect (Si)
%Daten.Totaleffek--> Total effect sensitivity indices (St)
%Daten.Integrationspotenzial--> Integration potential
%Daten.Einzelvarianz-->Partial variance (AVi)
%Daten.Varianz_nicht_i-->%Variance of complementary group (AVCi)
%Daten.Gesamtvarianz_X-->%Total variance (AV)

%OTHER USED VARIABLES/ CONSTANTS
%AC[] BC[]: Fourier coefficients
%V: Total output variance (for each curve)
%Vi: Partial variance of parameter i (for each curve)
%VCi: Partial variance of the complete set of parameter i
%AV: Total variance in the time domain
%AVi: Partial variance of parameter i in the time domain
%AVCi: Partial variance of the complete set of parameter i in
the time

%% Initialization
%Not second order effects in EFAST
%fillwithzeros is a variable to set or not a fill with zeros
%in the invalid networks
fillwithzeros = true;

Nr=1; %Defined in EFAST_Analyse
MF= 4; %MF is the maximun number of Fourier coefficients %that
may be retained in calculating partial variances %without inter-
ferences between the assigned frequencies.
wantedN=1000;
OMi=floor (((wantedN/Nr)-1)/(2*MF)/k);

for i1=1:k
    %Loading the results for each network parameter

    FileList = dir([ Pfad '\*Netz_Sample_EFAST_Parameter'
num2str(i1) '_Stichprobe*.mat']);
    Ursprungspfad  = cd;
    cd([Pfad '\']);
    Integrationspotenzial = zeros(size(FileList,1),1);
    Netznummern = zeros(size(FileList,1),1);
    Ungueltig = false(size(FileList,1),1);
```

```
if size(FileList,1)>1
    for i=1:size(FileList,1)
        A=FileList(i).name;
        %%Find NetzNr in the file names
        %in = regexprep(A,'\D+','');
        %NetzNr = str2num(in(1:end-8));
        in = find(A == '_');
        Netznummern(i) = str2num(A(in(5)+1+10:in(6)-1));
        load(FileList(i,1).name);
        Integrationspotenzial(i,1)=Ergebnis.Integration;
        Ungueltig(i,1) = any(~Ergebnis.Ergebnis_gueltig);

        clear Ergebnis
    end
else
    load(FileList.name);
    Integrationspotenzial=Ergebnis.Integration;
    Ungueltig = any(~Ergebnis.Ergebnis_gueltig);

    clear Ergebnis
end

cd(Ursprungspfad);


%% Deletion of invalid results

Ungueltige_Netze = Netznummern(Ungueltig,1);
Integrationspotenzial( Ungueltig,: ) = [];
Netznummern(Ungueltig,:) = [];


%% Assigning the result vectors
% X
kombiniert = [Netznummern, Integrationspotenzial];
kombiniert = sortrows(kombiniert,1);
if fillwithzeros && size(kombiniert,1)~=(2*MF*OMi+1)
    kombiniert_neu = zeros(2*MF*OMi+1,2);
    kombiniert_neu(:,1) = 1:(2*MF*OMi+1);
    for i = 1 : size(kombiniert,1)
        kombiniert_neu(kombiniert(i,1),2) = kombiniert(i,2);
    end
    kombiniert = kombiniert_neu;
end
Netznummern = kombiniert(:,1);
Integrationspotenzial = kombiniert(:,2);
y = Integrationspotenzial - mean(Integrationspotenzial);


%% Determination of the effects
```

```
    %Introduce the parameters that we use in the first code %in
the loops

    N= size(Integrationspotenzial,1); %2*MF*OMi+1; %Number %of
runs on each curve
    AVci=0;
    AVi=0;
    AV=0;

    %for i=1:k %for 1:k loop from EIKOS already implemented
%above (for i1 = 1:k)
    for L=1:Nr
        %Fourier coefficient at [1:OMi/2]

        if mod(N,2)
            Nq=(N-1)/2; %usually N is odd. in our case N %may be
even...
            N0 = Nq + 1;
            N00 = N0;
        else
            Nq = N/2;
            N0 = Nq;
            N00 = Nq + 1;
        end

        compl=0;

        y_vecp= y(N0+(1:Nq))+y(N00-(1:Nq));
        y_vecm= y(N0+(1:Nq))-y(N00-(1:Nq));

        for m=1:OMi/2
            angle=m*2*(1:Nq)*pi/N;
            c_vec=cos(angle);
            s_vec=sin(angle);

            AC(m)=(y(N0)+y_vecp'*c_vec')/N;
            BC(m)=y_vecm'*s_vec'/N;
            compl=compl+AC(m)^2+BC(m)^2;
        end

        %Computation of V_{(ci)}
        Vci=2*compl; %Partial variance of the complementary %set
of parameter i
        AVci=AVci+Vci;

        %Fourier coefficients at [p*OMi, for P=1:MF]
        compl=0;
        y_vecp=y(N0+(1:Nq))+y(N00-(1:Nq));
        y_vecm=y(N0+(1:Nq))-y(N00-(1:Nq));
        for n=OMi:OMi:OMi*MF
            angle=n*2*(1:Nq)*pi/N;
```

```
            c_vec=cos(angle');
            s_vec=sin(angle');

            AC(n)=(y(N0)+y_vecp'*c_vec)/N;
            BC(n)=y_vecm'*s_vec/N;
            compl=compl+AC(n)^2+BC(n)^2;
        end
        %Computation of V_i
        Vi=2*compl; %Partial variance of parameter i
        AVi=AVi+Vi;

        %Computation of the total variance
        AV=AV+y'*y/N;
    end

    AV=AV/Nr; %total variance in the time domain
    AVi=AVi/Nr; %Partial variance of parameter i
    AVci=AVci/Nr; %Partial variance of the complementary %set of
parameter i
    Si=AVi/AV; %First order sensitivity indices
    STi=1-AVci/AV;%Total effect sensitivity indices


    Daten.EFAST_Indices(i1) = Si; % EFAST indices
    Daten.Totaleffekt(i1) = STi; %Total effect sensitivity %in-
dices
    Daten.Integrationspotenzial{i1} = Integrationspotenzial;
    Daten.Einzelvarianz(i1) = AVi; %Partial variance
    Daten.Varianz_nicht_i(i1) = AVci; %Variance of complementary
group
    Daten.Gesamtvarianz_X(i1) = AV; %Total variance
end
end
```

Appendix C: Results

	Lenght beam	Number of radiating	Transformer Type	Distance to node link	Line type	Penetr. Single	Pentr. Building	Penet. Farms	Load appl. Factor	Inhomogeneity
EFAST Index	0,100036	0,048938	0,154564	0,038729	0,018105	0,011042	0,016332	0,00264	0,208379	0,023197
Total Effect	0,609921	0,380543	0,657612	0,29894	0,196133	0,179376	0,371906	0,135377	0,598759	0,326784
Partial variance	7878,916763	2072,28072	6638,049508	382,5325891	400,5494227	122,4514178	65,7749	38,78077	8002,051	231,126
Variance of complementary group	30722,97729	26231,20296	14704,49294	6924,568384	17784,23645	9100,150518	2529,517	12700,85	15408,24	6707,778
Total variance	78760,94471	42345,44915	42946,88692	9877,282474	22123,36709	11089,29997	4027,291	14689,46	38401,5	9963,788

Table 4: Values of a sample size of 1000 with filling zeros in invalid networks

	Lenght beam	Number of radiating	Transformer Type	Distance to node link	Line type	Penetr. Single	Pentr. Building	Penet. Farms	Load appl. Factor	Inhomogeneity
EFAST Index	0,014512285	0,006634442	0,03218406	0,016492395	0,008895981	0,013780434	0,015715	0,011813	0,105216	0,008939
Total Effect	0,236920798	0,287718858	0,17502393	0,063855958	0,023932087	0,116118954	0,113283	0,089243	0,555181	0,019409
Partial variance	1248,508742	327,8808863	1875,981473	175,8787426	217,8546316	176,6106699	82,85994	196,8296	4182,294	94,96182
Variance of complementary group	65648,58854	35201,66232	48087,15256	9983,258387	23903,03216	11327,85983	4675,47	15174,61	17681,34	10416,81
Total variance	86031,15954	49421,02248	58289,14842	10664,23322	24489,10762	12816,04564	5272,787	16661,53	39749,5	10622,99

Table 5: Values of a sample size of 1000 without filling zeros in invalid networks

	Lenght beam	Number of radiating	Transformer Type	Distance to node link	Line type	Penetr. Single	Pentr. Building	Penet. Farms	Load appl. Factor	Inhomogeneity
EFAST Index	0,020353444	0,021131344	0,008048333	0,023058675	0,032922799	0,030666127	0,007095	0,02967	0,010813	0,019779
Total Effect	0,599147007	0,658129499	0,718003204	0,527350345	0,462145377	0,722266702	0,548295	0,37923	0,75269	0,505962
Partial variance	380,0072596	604,3624287	231,3829549	517,988688	1123,866745	622,1714628	133,737	1058,945	174,295	878,6395
Variance of complementary group	7484,091856	9777,593376	8107,175655	10617,57321	18360,43558	5634,807778	8513,832	22155,56	3986,214	21946,5
Total variance	18670,41529	28600,28384	28749,1765	22463,93937	34136,42792	20288,55677	18848,23	35690,42	16118,29	44422,74

Table 6: Values of a sample size of 5000 with filling zeros in invalid networks

	Lenght beam	Number of radiating	Transformer Type	Distance to node link	Line type	Penetr. Single	Pentr. Building	Penet. Farms	Load appl. Factor	Inhomogeneity
EFAST Index	0,007883544	0,016233083	0,051254257	0,007587643	0,024063541	0,030806856	0,048497	0,005197	0,036939	0,052244
Total Effect	0,539222523	0,55638381	0,635786817	0,377003764	0,275357613	0,560255544	0,465337	0,264212	0,721883	0,395023
Partial variance	161,4160814	533,3003408	1704,502784	207,3310527	987,7968355	777,2160645	983,0864	190,85	702,6345	2680,084
Variance of complementary group	9434,448579	14573,98248	12112,21119	17023,2669	29746,2235	11094,16875	10838,14	27021,29	5290,264	31034,88
Total variance	20475,06453	32852,68396	33255,82861	27324,83106	41049,52185	25228,67225	20270,98	36724,28	19021,71	51299,31

Table 7: Values of a sample size of 5000 without filling zeros in invalid networks

	Lenght beam	Number of radiating	Transformer Type	Distance to node link	Line type	Penetr. Single	Pentr. Building	Penet. Farms	Load appl. Factor	Inhomogeneity
EFAST Index	0,013577379	0,022887097	0,014171508	0,015697557	0,023281942	0,015317047	0,056582	0,010689	0,006007	0,060834
Total Effect	0,817465437	0,762128366	0,739347079	0,671663839	0,747426624	0,635290817	0,674671	0,521414	0,632626	0,557031
Partial variance	342,1070507	747,1008322	416,2966105	399,3006768	551,6983401	575,4954358	1831,606	446,6163	157,9595	1770,825
Variance of complementary group	4599,294084	7764,815985	7656,837266	8351,927314	5985,081138	13702,93285	10531,25	19997,17	9660,02	12894,51
Total variance	25196,8395	32642,88329	29375,60507	25437,12301	23696,40549	37572,21775	32371,05	41783,85	26294,81	29109,31

Table 8: Values of a sample size of 7500 with filling zeros in invalid networks

	Lenght beam	Number of radiating	Transformer Type	Distance to node link	Line type	Penetr. Single	Pentr. Building	Penet. Farms	Load appl. Factor	Inhomogeneity
EFAST Index	0,018633424	0,095008323	0,05059188	0,013672245	0,023105783	0,051725223	0,014511	0,005451	0,001441	0,036806
Total Effect	0,858045867	0,751999179	0,753266268	0,580238862	0,570174125	0,308400401	0,457181	0,221967	0,656346	0,503862
Partial variance	536,4394703	3556,857474	1742,090332	425,8676909	607,7532704	2266,08359	600,9519	265,7792	42,87948	1284,437
Variance of complementary group	4086,731426	9284,487334	8496,075746	13074,86171	11305,74482	30298,99967	22480,75	37933,18	10223,05	17314,15
Total variance	28789,09793	37437,32498	34434,1882	31148,33777	26303,08104	43810,03072	41414,8	48755,23	29748,11	34897,85

Table 9: Values of a sample size of 7500 without filling zeros in invalid networks

	Lenght beam	Number of radiating	Transformer Type	Distance to node link	Line type	Penetr. Single	Pentr. Building	Penet. Farms	Load appl. Factor	Inhomogeneity
EFAST Index	0,029867103	0,060209489	0,012475536	0,0091225	0,009257363	0,028561198	0,058129	0,038102	0,005668	0,060125
Total Effect	0,784852975	0,75774225	0,907744113	0,728622188	0,74195908	0,883376128	0,798495	0,697776	0,811134	0,708519
Partial variance	681,424345	1395,713762	317,8070704	224,6525736	206,5191677	623,3677441	1357,034	945,4315	146,0851	1555,688
Variance of complementary group	4908,625372	5615,767254	2350,165343	6683,005862	5756,54189	2545,396012	4704,146	7499,039	4868,114	7541,89
Total variance	22815,21375	23180,96013	25474,42127	24626,20581	22308,63962	21825,68606	23345,03	24812,86	25775,51	25874,41

Table 10: Values of a sample size of 10000 with filling zeros in invalid networks

	Lenght beam	Number of radiating	Transformer Type	Distance to node link	Line type	Penetr. Single	Pentr. Building	Penet. Farms	Load appl. Factor	Inhomogeneity
EFAST Index	0,011876893	0,02746543	0,059650558	0,126157493	0,016963369	0,08768847	0,00642	0,06898	0,006916	0,053825
Total Effect	0,759394499	0,704723135	0,821300332	0,649726008	0,578303623	0,837148452	0,748423	0,583801	0,746412	0,718036
Partial variance	321,7412945	782,9233279	1893,467752	3598,83188	441,6754697	2252,757798	172,4583	1947,604	203,2851	1596,845
Variance of complementary group	6517,927335	8417,095418	5672,403956	9992,091447	10979,71452	4183,732443	6758,218	11751,03	7453,803	8365,067
Total variance	27089,68543	28505,77344	31742,66639	28526,50119	26037,01412	25690,46775	26863,47	28234,17	29393,37	29667,11

Table 11: Values of a sample size of 10000 without filling zeros in invalid networks

	Lenght beam	Number of radiating	Transformer Type	Distance to node link	Line type	Penetr. Single	Pentr. Building	Penet. Farms	Load appl. Factor	Inhomogeneity
EFAST Index	0,01584655	0,006561828	0,028007544	0,043308437	0,017201532	0,057522094	0,020409	0,063025	0,025437	0,019745
Total Effect	0,801496236	0,808917851	0,878545239	0,803864611	0,763300144	0,896479114	0,80061	0,683517	0,84779	0,722012
Partial variance	329,4836003	159,4654618	755,5483934	1036,730433	495,0156869	1320,365144	457,4727	1309,711	669,9604	659,2611
Variance of complementary group	4127,316956	4643,675746	3276,436915	4695,148091	6811,610983	2376,223837	4469,424	6576,78	4008,983	9281,758
Total variance	20792,13452	24301,98619	26976,60331	23938,30154	28777,41926	22954,05232	22415,54	20780,81	26338,43	33389,06

Table 12: Values of a sample size of 12500 with filling zeros in invalid networks

	Lenght beam	Number of radiating	Transformer Type	Distance to node link	Line type	Penetr. Single	Pentr. Building	Penet. Farms	Load appl. Factor	Inhomogeneity
EFAST Index	0,054458223	0,008755574	0,018085583	0,013416021	0,073645069	0,024767301	0,041543	0,05192	0,004555	0,040076
Total Effect	0,829742547	0,776954105	0,763023409	0,778364283	0,713823911	0,837970597	0,771142	0,68189	0,793048	0,694814
Partial variance	1318,994536	254,3052756	568,3797804	373,2444741	2622,114302	663,8273878	1057,128	1232,611	140,7028	1507,605
Variance of complementary group	4123,686705	6478,358272	7447,517919	6166,083741	10189,22823	4342,804926	5823,693	7552,087	6393,372	11480,73
Total variance	24220,30073	29044,95629	31427,23036	27820,80357	35604,75042	26802,57319	25446,7	23740,5	30892,95	37618,75

Table 13: Values of a sample size of 12500 without filling zeros in invalid networks

	Lenght beam	Number of radiating	Transformer Type	Distance to node link	Line type	Penetr. Single	Pentr. Building	Penet. Farms	Load appl. Factor	Inhomogeneity
EFAST Index	0,014848026	0,036991444	0,069316896	0,042841212	0,047917543	0,024207663	0,07006	0,049043	0,010808	0,027209
Total Effect	0,880158239	0,844324373	0,939589366	0,846844231	0,908107994	0,892446589	0,787011	0,846886	0,819818	0,928754
Partial variance	280,1516827	806,9660127	1705,919808	1126,676739	1347,454529	557,013925	1934,014	1057,851	208,3881	617,874
Variance of complementary group	2261,167292	3396,053914	1486,732715	4027,828183	2584,028554	2474,784473	5879,563	3302,661	3474,211	1617,903
Total variance	18867,9411	21814,93652	24610,44727	26298,89948	28120,27582	23009,81867	27605,02	21570,01	19281,71	22708,7

Table 14: Values of a sample size of 15000 with filling zeros in invalid networks

	Lenght beam	Number of radiating	Transformer Type	Distance to node link	Line type	Penetr. Single	Pentr. Building	Penet. Farms	Load appl. Factor	Inhomogeneity
EFAST Index	0,02744551	0,017595294	0,030832159	0,022617249	0,090844364	0,035234049	0,05425	0,050646	0,010301	0,04345
Total Effect	0,856500714	0,843772566	0,823386673	0,845143177	0,815888078	0,845505176	0,703632	0,690263	0,812337	0,879213
Partial variance	616,8253165	459,2338931	887,5227929	686,8319425	2999,483222	934,8656774	1639,904	1320,872	243,6452	1170,529
Variance of complementary group	3225,081006	4077,506824	5083,923945	4702,632615	6078,97504	4099,214097	8958,745	8078,022	4438,536	3253,934
Total variance	22474,54393	26099,81308	28785,619	30367,61653	33017,82409	26533,01897	30228,46	26080,28	23651,67	26939,54

Table 15: Values of a sample size of 15000 without filling zeros in invalid networks